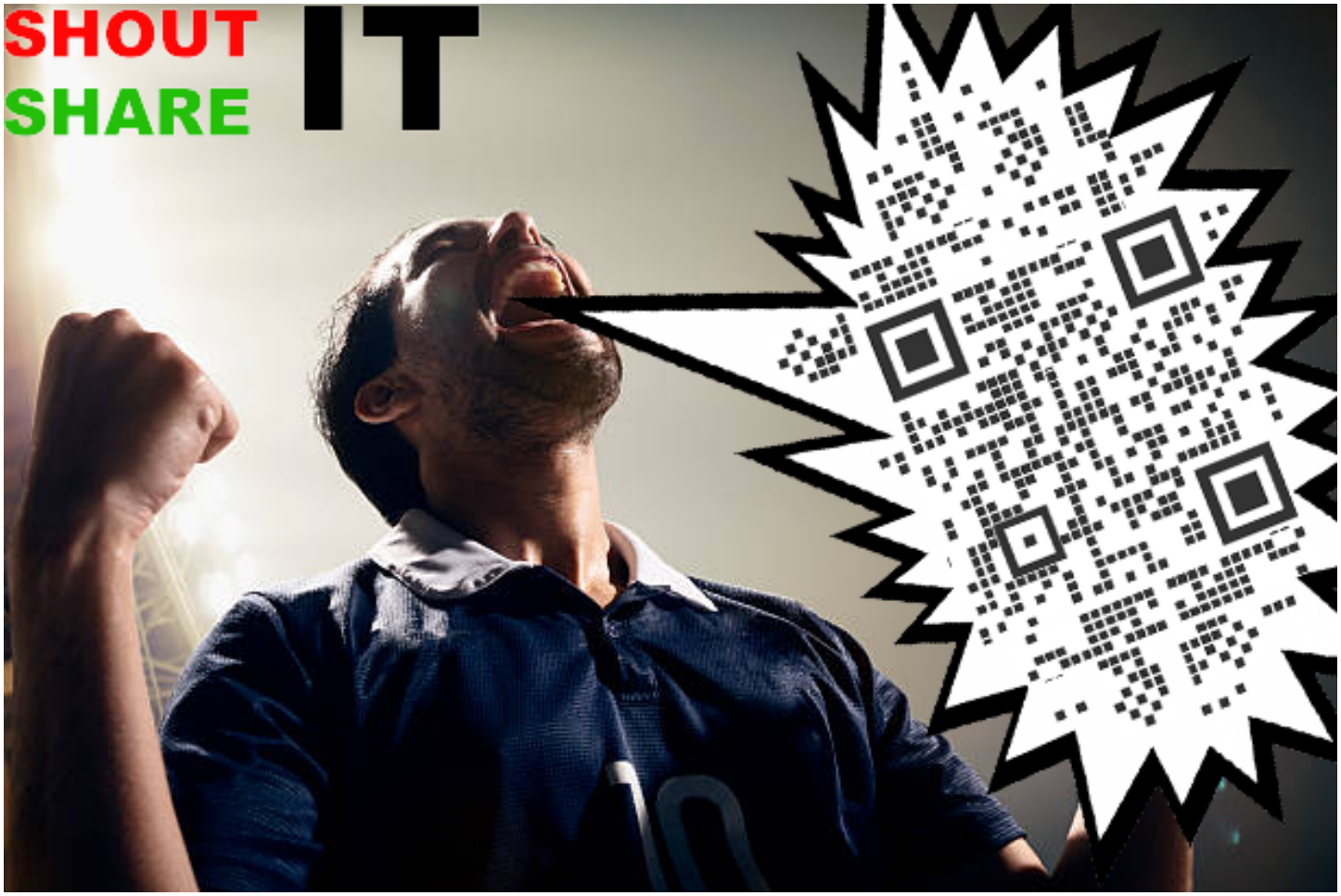
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BULLETIN OF THE GEOLOGICAL SOCIETY OF NORFOLK

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No. 27

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"Lyelliana"

DOUBLE ISSUE

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BULLETIN of the GEOLOGICAL SOCIETY OF NORFOLK 1
No. 27 April 1975
Editor: R.S. Joby
116 Gowing Road, Norwich NR6 6UQ

EDITORIAL

Our President, Hywel Evans, gave us an illustrated view of some of his recent research into the tills of the Bawsey district, near King's Lynn. We are now happy to print a summary of that talk and invite comment and rejoinders on the content. Hywel has also started an annual lecture for the society at King's Lynn with our western members in mind, a noteworthy innovation which we wish well.

This edition is a double edition for a number of reasons. Our production editor, Brian Funnell, will be away at the time when the autumn edition would normally go to press and also the impending vast increase in postal charges can be minimised by combining two editions. I hope this meets with members' approval.

Our numerous contributions this time cover the county from east to west from several points of view. We have also included some 'Lyelliana' to mark the Centenary of the death of Sir Charles Lyell, a not infrequent visitor to Norfolk, and observer of its geology.

Five contributors have started work on the 'New Geology of Norfolk' with sections to be issued as separate booklets as the manuscripts become available. These will then be bound into a single volume on completion of the series.

Bulletin No. 28 will be issued in April 1976. Contributions should be sent to me as soon as possible, and

to be certain of inclusion, no later than 30 September 1975. Will contributors please note that manuscripts are acceptable in legible handwriting, although typewritten copy is preferred. In either case it would be a great help if details of capitalisation, underlining, punctuation, etc., in the headings and references (particularly) could conform strictly to those used in the Bulletin. Otherwise publication may be delayed.

Illustrations intended for reproduction without redrawing should be executed in thin, black ink line. Thick lines, close stipple, or patches of black are not acceptable, as these tend to spread in the printing process employed. Original illustrations should, before reproduction, fit into an area of 225 mm by 175 mm; full use should be made of the second (horizontal) dimension, which corresponds to the width of print on the page, but the first (vertical) dimension is an upper limit only. All measurements in metric units, please.

R.S.J.

Bull. geol. Soc. Norfolk, 27, 3 - 19 (April 1975)

THE SUB-MESOZOIC FLOOR IN NORFOLK

P.N. CHROSTON* and M. SOLA

Introduction

The general features of the sub-Mesozoic floor in Eastern England are well known. In East Anglia the floor forms part of the London-Brabant Massif and comes to within 150m of the surface. The overlying Mesozoic rocks are thin compared to Lincolnshire and to southern England, and it appears that the Massif has been a relatively stable area since the late Devonian.

Various aspects of the geology of the floor have been discussed by a number of authors. Bullard et al. (1946) conducted seismic refraction measurements around Cambridge and reviewed the available borehole data in the East Anglia region. A contour map of the sub-Permian floor was included in Kent (1949), and in a later paper, Kent reviewed the general geology of the sub-Mesozoic floor in Eastern England (Kent 1968). An account of the Caledonian igneous rocks in Central and Eastern England has been given by Le Bas (1972). Recently, an important contribution has been the production of a map of the sub-Mesozoic (strictly sub-Upper Permian) geology in southern Britain by Professor Wills (1973).

In these and in other papers, however, information on the geology of the sub-Mesozoic floor of the northern part of East Anglia is scant, and it is the purpose of this short article to review additional information now available. The results of deep boreholes and geophysical surveys are described, and, as any proper attempt at

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understanding the floor in Norfolk must take account of information from a much wider area, data from outside Norfolk is included.

Deep boreholes

Deep boreholes in East Anglia show a variety of rock types ranging from Precambrian to Permian in age beneath the Mesozoic cover. In the south-east, boreholes at Harwich, Sutton and Weeley show steeply dipping rocks which were deposited as mudstones and siltstones. The age of the rock is certainly lower Palaeozoic and is possibly upper Silurian (Bullard et al. 1946). Further south, in the London area, numerous boreholes have revealed Palaeozoic rocks. Most of these are Devonian sediments but a few show Silurian (Wills 1973). In central Suffolk a boring at Culford shows "a greenish-grey slaty rock" at 161 m below O.D., beneath Lower Greensand (Whitaker and Jukes-Brown 1894). It is possibly comparable to the Palaeozoic rocks found in the bores around Harwich (Bullard et al. 1946) and is marked as Silurian on the Tectonic Map of Great Britain (Institute of Geological Sciences 1966a). At Cambridge, Carboniferous Limestone was found in bores carried out by the IGS (Edmunds 1954), and at Soham, to the north-east of Cambridge, an IGS borehole penetrated Devonian. At Warboys in Huntingdonshire, a borehole was put down by the Institute to investigate the cause of distinct gravity and magnetic anomalies. The borehole penetrated diorite below Lower Liassic at a depth of 170 m below O.D. (Institute of Geological Sciences 1966b). Le Bas (1972) has briefly described the rock and suggests that the diorite is probably a Caledonian intrusion. Another IGS borehole close by to the north of the Warboys site, at Upwood, showed volcanic agglomerate (?Precambrian) beneath Keuper Marl (Institute of Geological Sciences 1966b), whilst two others, at Huntingdon and Great Paxton, showed mudstones and siltstones of Llanvirnian

age beneath Lower Lias (Stubblefield 1967, Institute of Geological Sciences 1967).

The the northen part of East Anglia, however, knowledge of the geology of the sub-Mesozoic floor has relied heavily on the two widely spaced and well-known boreholes at Lowestoft and North Creake.

At Lowestoft the borehole, put down for water supply investigations, penetrated dark hard mudstones below Lower Greensand at a depth of 492 m below O.D. (Whitaker 1906). The rocks are generally described as Lower Palaeozoic (see e.g. Wills 1973), but the age is somewhat uncertain and indeed it might be younger (Stubblefield 1967).

The North Creake borehole is perhaps one of the most important boreholes in Norfolk. It was carried out in 1946 by the D'Arcy Exploration Company and its position gave critical control to the interpretation of the sub-Mesozoic rocks of the Midlands and East Anglia. At a depth of 733 m ,Bunter sandstone rested on a "dark greenish grey, somewhat sheared tuff" (Kent 1947, p. 12). The rocks resemble the agglomerate or tuff found in Leicestershire and were therefore ascribed to the Precambrian. Deep boreholes between Leicester and North Norfolk at Foston, Sproxton and Glinton have also shown similar rock types beneath the Mesozoic, demonstrating the presence of a ridge, largely of Precambrian rocks, extending between these two areas.

Apart from those described above, other deep bores have been carried out in the last ten years as part of the North Sea oil and gas exploration programme. Although it was well known from the previously established borehole and geophysical data that the thickness of the post-Palaezoic sediments was small, and that the Palaezoic rocks themselves were of doubtful importance in the search, there was always the possibility that gas may be stratigraphically trapped in the Mesozoic succession. Also the wells were important for obtaining information on the

general stratigraphy of the area. New data on the sub-Mesozoic rocks from seven oil company wells in East Anglia is given below. The data is based entirely on the well logs of the companies concerned. Their locations are shown in Fig. 1.

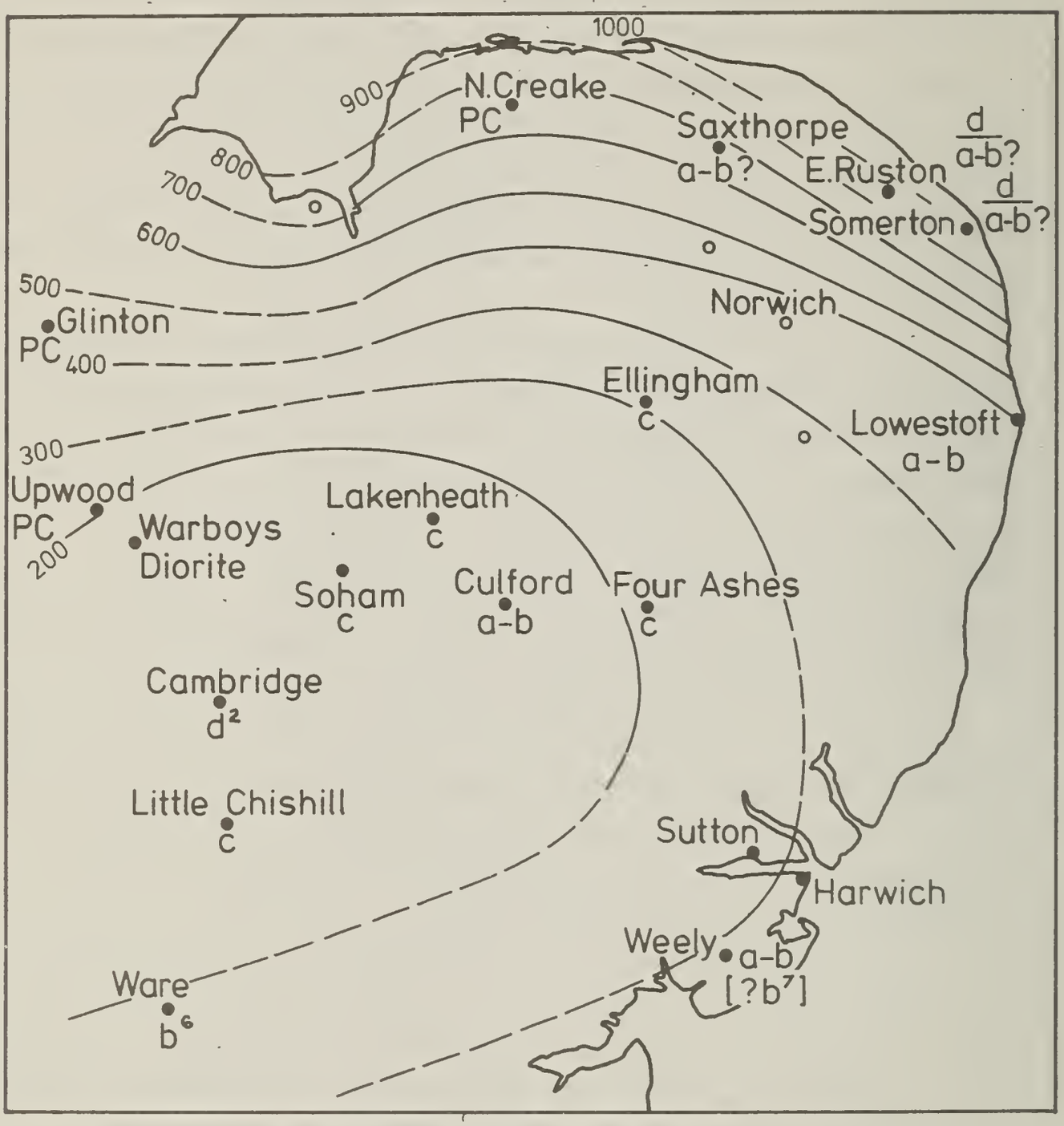

Fig. 1. Deep boreholes (solid circles), University of East Anglia seismic refraction lines (open circles), and depth to the sub-Mesozoic (strictly, sub-Permian) floor in East Anglia. Contour interval 100 metres. Key to ages: PC, Precambrian; a-b, Lower Palaeozoic b^{6-7}, Silurian; c, Devonian; d, Carboniferous.

(i) Little Chishill (Essex)

At a depth of 147 m below O.D. the Mesozoic rocks rested on a maroon mudstone, hard, massive and fossiliferous, with a light grey shaly limestone, hard,and with brachiopods and other fossils. The bedding was virtually horizontal and the rock has been dated as Devonian. The borehole is about 10 km to the south of Cambridge, where the Carboniferous Limestone is known to form the top of the Palaeozoic floor.

(ii) Four Ashes (Suffolk)

Here the floor consts of a dark grey shale with streaks of siltstone at a depth of 217 m below O.D. The shale had a dip of approximately 35°, and it was ascribed to the Devonian.

(iii) Lakenheath (Suffolk)

The Mesozoic rocks rest on a hard grey-green to maroon siltstone. The siltsone has some contorted beds and local fracture planes at a dip of 50°, but the bedding is horizontal. The depth at the unconformity was 188 m below O.D. Below 210 m the siltstone alternated with a grey hard silty shale. The age is possibly Devonian.

(iv) Ellingham (Attleborough, Norfolk)

This borehole has been included on Professor Wills' fine map (Wills 1973). Rocks of probable Devonian age are found at 309 m below O.D. They consist mainly of a green, hard, massive mudstone with marked fracture planes and a dip of 50-55°. Beneath 329 m the lithology changes to a dark grey, hard slate.

(v) Saxthorpe (Norfolk)

Beneath a thick Permo-Triassic sequence, Lower Palaeozoic rocks, tentatively dated as Silurian, are found at a depth of 771 m. The borehole penetrated some 162 m of shales, siltstones, mudstones, and fine silty sandstones. A core showed an apparent dip of 30-40°, with a poorly developed vertical cleavage.

(vi) East Ruston (Norfolk)

East Ruston lies close to the north-east coastline of Norfolk, and some 15 km from Saxthorpe. In this distance there is, however, a dramatic change in the lithology of the Palaeozoic floor. At the bottom of the Permo-Triassic sandstones, and at a depth of 995 m below O.D., a basal conglomerate rests on top of Carboniferous Limestone. About 100 m of this rock is present and it is generally a white to pale-tan, fossiliferous, dolomitic limestone, locally red stained and in places oolitic. In parts, clay and silty shale bands are present. Below 1095 m there is a Lower Carboniferous sandstone and shale unit and this rests on what is possibly Lower Palaeozoic at 1109 m. Some 396 m of this latter rock was penetrated and the lithology appears very similar (from the log description) to the Lower Palaeozoic of the Saxthorpe borehole, being a sequence of shales, mudstone, siltstones and fine sandstones. No palaeontological evidence of the age is available.

(vii) Somerton (Norfolk)

This deep boring also lies close to the coast of north-east Norfolk, and is only some 7 km from the borehole at East Ruston. Beneath Permian sandstone (Rotliegende), at a depth of 978 m below O.D., are 43 m of Barren Red Measures (Carboniferous). These are red and grey clays, siltstones and shales. These follow some 18 m of Lower Westphalian clays above a thick (139 m) dolomitic limestone sequence. This is similar to the East Ruston Limestone, being cream, brownish, hard and massive, and fossiliferous. In places mudstone is present, and also traces of fine sandstone. An interesting feature is the extensive mineralization in the upper part of the limestone with galena, pyrites and marcasite being present.

Below the limestone, at a depth of 1180 m, a sequence of sandstones, siltstones and shales extend down to 1370 m below O.D. This and the limestone sequence are known from palaeontological evidence to be Visean (S + D zones).

Below the Carboniferous, a hard blue grey to dark grey shale and siltstone with slaty cleavage and dips up to 70° was encountered. It was tentatively ascribed to the Lower Palaeozoic (?Silurian).

Superficially, there does not appear to be any great difference in lithology between the rocks described as Lower Palaeozoic and those described as Devonian. The former (Harwich, Sutton, Weeley, Culford, ?Lowestoft, Saxthorpe, Somerton) could be described as typically "geosynclinal", the rocks including fine mudstones, shales and slates, with thin silt bands. However, the Devonian rocks from Lakenheath, Four Ashes and Ellingham show similar lighologies (from the borehole logs) with shales, and slates and siltstones. The writer has not examined the cores from the above boreholes, but a detailed examination might reveal significant differences in lithology between the Devonian and Lower Palaeozoic rocks. A quite distinctive lithology is of course found for the Devonian of Little Chishill, which shows a considerable amount of limestone (indicating a shallow marine environment?).

Much of the dating of the borehole data is somewhat tentative, though Devonian dates appear to give Middle or Upper Devonian (see Wills 1973). Structurally also there is no clear division. Although Professor Wills tentatively describes the pre-Carboniferous geology to the south-west as "gently folded thin ORS/Dev. on sharply folded and faulted Lower Palaeozoics" steep dips are found for both in the boreholes.

The boreholes situated on the north-east Norfolk coast appear to be at the point where there is extensive thickening of the Carboniferous sequence into the North Sea basin. The Carboniferous limestone found at Cambridge in evidence for an extensive marine transgression at that time, but the original cover of limestone seems at least to have been thin and perhaps discontinuous (Kent 1968).

The new borehole data described above suggest some modification to Professor Wills' map of the sub-Mesozoic

geology. The boreholes at Lakenheath and Four Ashes show that the Devonian rocks may well extend some way to the south-west from Attleborough (Ellingham borehole), and indeed, there may be a virtually complete cover of Devonian to Soham, with the Lower Palaeozoics of Culford being surrounded by the younger rock. Also, the borings at East Ruston and Somerton show Carboniferous rocks encroaching into the north-east of Norfolk. It should be stressed however, that the dating of the sub-Mesozoic rocks in several of the boreholes is somewhat tentative, and accurate palaeontological dating may result in significant changes.

Geophysical data

Geophysical data available and relevant to the study of the sub-Mesozoic floor in Norfolk includes gravity and aeromagnetic anomaly maps published by the Institute of Geological Sciences and seismic refraction data obtained by members of Cambridge University (Bullard *et al*. 1946) and by the University of East Anglia (Sola 1974).

The seismic refraction experiments carried out by Bullard *et al*.(1946) covered an extensive area in the central part of East Anglia and enabled a contoured map of depth to the sub-Mesozoic floor to be made. The programme of seismic studies being carried out by the University of East Anglia is aimed at extending the Cambridge studies into Norfolk, with the eventual object of producing a more detailed map of depth to the floor than can be obtained by the boreholes alone. Also, by analysing the distribution of velocities of the sub-Mesozoic floor refractor, it is hoped to obtain further information on the geological nature of the refractor.

There are certain limitations in the use of the seismic refraction method in the calculation of depth to the refractor and the calculated depth may only be approximate. The IGS boreholes at Wybostan and Soham, for example, demonstrated the sub-Mesozoic floor to be at a depth which was less than had been predicted by the

seismic method (Bellerwell, in Stubblefield 1967). However the difference between predicted and proven depth in East Anglia appears to be generally small. In Fig. 1 a contoured surface of depth to the sub-Mesozoic floor is shown. For the southern part of East Anglia, it is based largely on the depths from borehole data, but in the north some provisional University of East Anglia seismic results have been used.

The velocities of the compressional wave in the refractor vary fron 3.5 to 6 km. s^{-1}. The high velocities (6 km. s^{-1}) are found in the north and a correlation with the Precambrian volcanic rocks is possible. The lowest velocities (3.5 to 4.5 km. s^{-1}) are found in the Cambridge area. Carboniferous Limestone has been shown here (Edmunds 1954), but the seismic sites giving the velocities extend over a fairly wide area, and the Little Chishill borehole close to them shows Devonian as the refractor. Two seismic lines in Norfolk (Sola 1974), and a number in N.W. Suffolk (Bullard et al.1946) show the refractor to have a velocity of 4.7 - 5.4 km. s^{-1}. Boreholes in the vicinity here however (Lakenheath, Culford, Four Ashes), show the rock of the sub-Mesozoic floor to have lithologies comparable to Little Chishill (mudstones, silts, slates). The reason for the difference in velocity is not clear. A great many more seismic lines are required in the region before even fairly simple maps of the geology based on the velocities can be made. In particular, some seismic lines situated in the south-eastern part of East Anglia are highly desirable.

The aeromagnetic map, reproduced in Fig. 2, potentially provides considerable information on the sub-surface geology. A prominent feature is the complex pattern of magnetic anomalies with steep flanking gradients and high amplitudes extending in a belt some 30 km wide from the Wash to Leicester. The steep gradients indicate a shallow depth to the rock type causing the anomalies. The most likely source for the anomalies is the Precambrian volcanics found in the deep boreholes in this area (North

Creake, Glinton, Upwood) but it is quite possible that Caledonian intrusion (of which Warboys diorite is evidence) may also contribute. Furthermore, basement topography in addition to intra-basement magnetization contrasts can also give rise to magnetic anomalies.

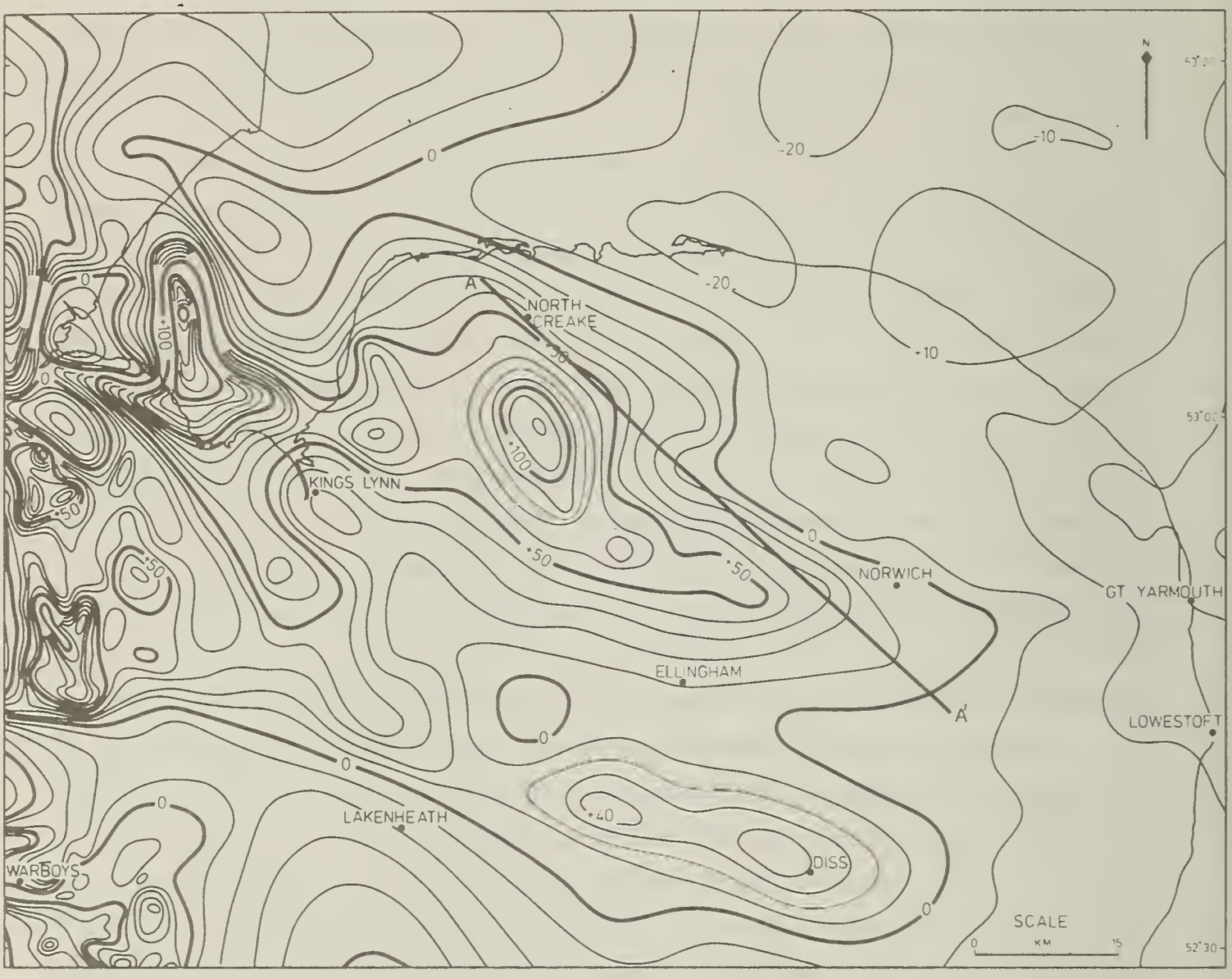

Fig. 2. Aeromagnetic anomaly map of the northern part of East Anglia. Contour interval 10 gammas.

Although the boreholes in this belt of anomalies have revealed only the Precambrian, the possibility of Palaeozoic sediment existing somewhere within the structurally complex ridge cannot be ruled out. However, although the pattern of anomalies to the west of the Wash is complex and difficult to interpret, that over East Anglia is simpler, the anomalies being of wide extent

and having gentle gradients. This is normally taken to indicate a deeper magnetic basement which in this case is assumed to be the Precambrian. Although it is true that there could be intrusions in the Palaeozoic strata, they would form distinct magnetic anomalies (as at Warboys). The Palaeozoic mudstones and siltstones found in the boreholes in East Anglia can be assumed to have a negligiable magnetization, and it is possible that the magnetic basement could be at least 3000 m (10,000 feet) deep (Kent 1968).

In the north of the area the level of the anomaly reaches +100 gammas close to North Creake and a prominent anomaly extends south-east from the Wash towards Norwich. This can be interpreted as a ridge of Precambrian within the sub-Mesozoic floor extending and deepening in this direction. Professor Wills, in his sub-upper Permian map, has tentatively shown Precambrian exposed on the floor in this area.

The Mesozoic sediments have a marked density contrast to the sub-Mesozoic rocks, and with the steady and marked increase in depth to the floor towards the north coast, one might expect that the Bouguer anomalies would show a marked reduction (see Fig. 3). This is partly true in that across the central part of East Anglia a broad but positive anomaly with an average value of +3 to +5 mgal, is found, and overall there is a reduction to the north coast where values of -1 mgal are typical. However the picture is somewhat complicated by a distinct 'low' centered on Guist and Reepham in north-central Norfolk where values of -6 mgal are observed. Also to the west, around the Wash, the Bouguer anomaly pattern is complex.

A gravity survey of the Wash by Sola (1974) demonstrated the presence of a small positive central gravity anomaly with a relative amplitude of 10 mgal. The anomaly appears to be an extension of the positive axis to the south east of Kings Lynn, and over the Wash the gravity anomaly coincides approximately with the position of a

distinct 200 gamma positive magnetic anomaly. The interpretation of the gravity and magnetic anomalies in this western area is difficult. There is, in places, a close relationship between the gravity and magnetic anomalies suggesting a common geological cause. Over the Wash, interpretation of the anomalies leads to the conclusion that simple topography of the sub-Mesozoic floor is insufficient to cause the anomalies and it can be demonstrated that there must be an intra-basement density and/or magnetization contrast (Sola 1974). An intrusion is possible, but the extension of the gravity anomaly to the south-east suggests some tectonic control.

Fig. 3 Bouger anomaly map of the northern part of East Anglia.

It is likely that much of this western area can be similarly interpreted and that both basement topography and the varied geology within the basement can contribute to the anomalies. The problem of interpretation would be eased considerably by detailed information on basement topography, and it is hoped that seismic work in progress in the area of the Wash will be of help in the interpretation of the anomaly there.

In the rest of Norfolk there is not an obvious correlation between the gravity and magnetic anomalies. This is partly to be expected, as the magnetic anomalies will be largely dependent on the topography and character of the Precambrian basement, whilst the gravity anomalies will be affected by the whole of the sub-Mesozoic floor. The construction of models to explain both the anomalies is difficult, as there is little doubt that significant changes in the physical properties may occur within both the Precambrian, and the Palaeozoic sediments in the area. The problem is illustrated in the sketch interpretation of the gravity and magnetic profiles between North Creake and Lowestoft (Fig. 4, from Sola 1974). Using reasonable density contrasts, of 2400 kg m^{-3} for the post-Palaeozoic rocks, 2550 kg m^{-3} for the Palaezoic sediments and 2800 kg m^{-3} for the Precambrian, a wedge of Palaezoic sediment in north Norfolk can be used to explain the gravity low there. However, there is only a fair comparison with the magnetic anomaly profile which suggests that the Precambrian floor in the south-east lies at a much greater depth than that indicated by the gravity profile. With the constraints of known geology and sub-Mesozoic floor topography, there has to be regional variation of the densities and/or magnetizations of the major rock divisions used in the model, in order to satisfy the observed gravity and magnetic anomalies.

An attempt at analysing the major tectonic features of the area, without resort to producing models, was made by Linsser (1968). His technique involved comparing

profiles from the anomaly maps with large families of computed anomalies due to simple structures at varying depths. The structure he used was the infinitely thin half plate (corresponding to a fault). Although the method produced some interesting tectonic trends, calculation of depth to the "faults" produced very high values.

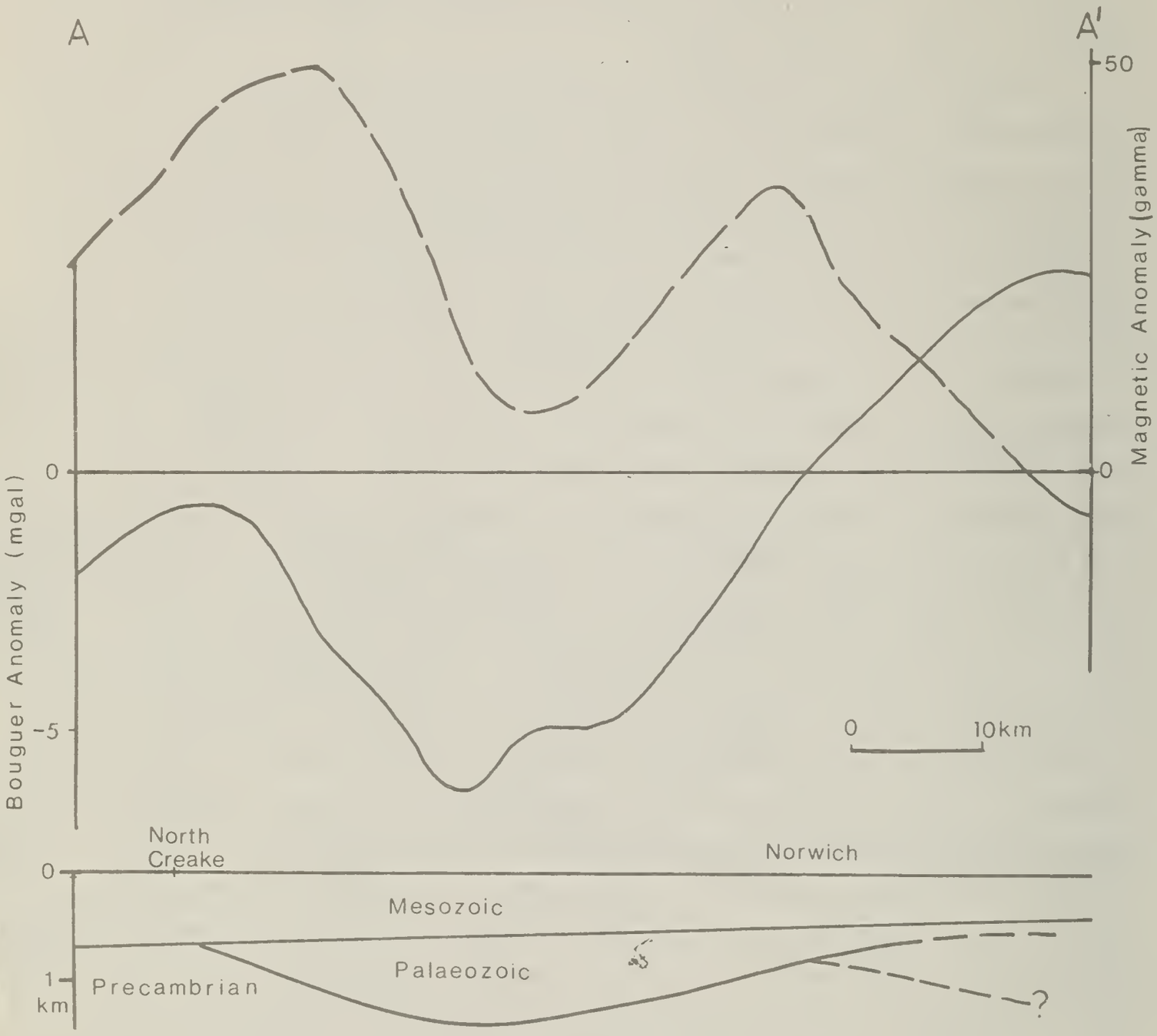

Fig. 4 Bouguer anomaly, total field magnetic anomaly, and sketch geological section along the line AA'. The lower dashed line in the geological section to the south-east indicates the approximate position of the Precambrian surface based on the magnetic anomaly at this point.

In the Wash for example, depths of over 4 km were obtained, whereas it can be calculated by the method of Bruckshaw and Kunaratham (1963) that the maximum depth to the top of the anomaly causing body is approximately 2.0 km. Depths of over 10 km to the magnetic basement were common in Linsser's analysis over East Anglia and this seems unreasonably high. However, by combining more significant results of such an analysis as this with the simple modelling, it might be possible to delineate areas of particular interest and worthy of more detailed geophysical study.

The new borehole data has provided important new information on the nature of the sub-Mesozoic floor, and it is also of considerable importance as control for the interpretation of the geophysical data. The latter potentially provides the only practical way of examining the gross structure actually within the London-Brabant massif. However, it is clear that the relationship between Bouguer anomaly, magnetic anomaly, seismic velocity and lithology of the floor is complex. Further seismic refraction measurement together with deep drilling in carefully selected areas is needed before the relationships can be fully understood. There is apparently a distinct contrast in compressional wave velocity between the Precambrian volcanics and the Palaeozoic sediments and carefully controlled seismic refraction lines along the axis of the positive magnetic anomaly in Norfolk might well be rewarding.

Acknowledgement

I am most grateful to Conoco (Europe) Ltd. and to Superior Oil Co. Ltd. for allowing me to publish details of their boreholes in East Anglia. The aeromagnetic and Bouguer anomaly maps (Figs. 2 and 3) are reproduced with kind permission of the Institute of Geological Sciences.

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Received February 1975

Sir Charles LYELL (1797-1875)
- extract from his 'Principles of Geology' 1867, pp. 511-2, 513.

Norfolk.—The decay of the cliffs of Norfolk and Suffolk is incessant. At Hunstanton, on the north, the undermining of the lower arenaceous beds at the foot of the cliff, causes masses of red and white chalk to be precipitated from above. Between Hunstanton and Weybourne, low hills, or dunes, of blown sand, are formed along the shore, from fifty to sixty feet high. They are composed of dry sand, bound in a compact mass by the long creeping roots of the plant called Marram (*Arundo arenaria*). Such is the present set of the tides, that the harbours of Clay, Wells, and other places are securely defended by these barriers; affording a clear proof that it is not the strength of the material at particular points that determines whether the sea shall be progressive or stationary, but the general contour of the coast.

On the same coast, says Mr. R. C. Taylor, the ancient villages of Shipden, Wimpwell, and Eccles have disappeared; several manors and large portions of neighbouring parishes having, piece after piece, been swallowed up; nor has there been any intermission, from time immemorial, in the ravages of the sea along a line of coast twenty miles in length, in which these places stood.‡ Of Eccles, however, a monument still remains in the ruined tower of the old church. So early as 1605 the inhabitants petitioned James I. for a reduction of taxes, as 300 acres of land, and all their houses, save fourteen, had then been destroyed by the sea. Not one half that number of acres now remains in the parish, and hills of blown sand called 'Marrams' now occupy the site of the houses which were still extant in 1605. When I visited the spot in 1839, I found the tower of the church half buried in the dunes of sand, as represented in the drawing (fig. 43), and twenty three years afterwards my friend the Rev. S. W. King made a sketch from nearly the same spot which is given in fig. 44. In the interval the sand dunes,

Bull. geol. Soc. Norfolk, 27, 21 - 27 (April 1975)

THE BASE OF THE CARSTONE AT HUNSTANTON - PART II

R.W. GALLOIS*

Following the successful excavations to examine the base of the Carstone made at Hunstanton beach on 22nd October 1972 (Gallois 1973), a second field excursion and series of excavations was organised by Mr. Hamon Le Strange on 17th June 1973 to try to provide details of those parts of the Barremian - Albian sequence that were still in doubt.

Prior to the digging of the first excavation the nature of the base of the Carstone was thought to be relatively simple. The Carstone (probably Lower Albian in age) was thought to rest with marked unconformity, and with striking lithological change, on the Snettisham Clay (Lower Barremian), with a nodule bed at the base of the Carstone containing derived Lower Greensand (Lower Aptian) phosphatized ammonites. Much rarer blocks of very fossiliferous sandy phosphatic ironstone of Barremian age were also known from Hunstanton beach and were thought to occur in the same nodule bed as the derived Aptian fauna, the two types of nodule testifying to the former presence in Norfolk of a much thicker pre-Carstone Cretaceous sequence than can now be seen.

The 1972 excavations showed that this interpretation was much oversimplified; the fossiliferous nodule bed at the base of the Carstone was by no means as continuous as had been imagined and the Carstone was underlain by about 1.5 metres of very sandy oolitic pebbly clay. This clay was lithologically similar to parts of the Roach of Lincolnshire (probably Middle and Upper Barremian) and quite unlike the Snettisham Clay. The pebbly clay was underlain by very fine-grained sands, and separated

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from them by an erosion surface. The sands yielded a few indigenous sandy phosphatic ironstone concretions which contained pieces of wood and a few shells, including an ammonite fragment of Barremian affinities.

The purpose of the new excavations was to obtain further information about the nature of the contact of the pebbly clay and the fine-grained sands; the indigenous and/or derived faunas of the pebbly clay and the source of the very fossiliferous phosphatic ironstone of Barremian age.

Results

Four trenches were dug with a JCB 3C seaward of the outer Carstone reef and close to excavations (3) and (4) of 1972 (Gallois 1973, Fig.1). Two of these trenches (at TF 67144156 and TF 67074156) were abandoned due to inflow of water from the overlying beach sands and gravels. In this respect future excavators may be interested to note that the more inviting parts of the beach (those which dry out at low tide) are underlain by waterlogged gravelly sands, whereas those areas where the clays are close to the surface remain permanently wet. Successful excavations were made at TF 67124152 and TF 67054168.

The combined results of the 1972 and 1973 excavations are summarised below and in Fig. 1. It should be noted that the bed numbers referred to here differ from those in Gallois 1973. This is because, in the later excavations, it became clear that Beds (2) and (3) of the 1972 excavations were part of a single bed of variable lithology.

The sequence can be summarised as follows:-

RECENT:	Beach sand, gravelly in places	0.30 to 0.50m
CARSTONE:	Bed (4): Fine-grained, orange-brown, pebbly, oxidised and rotted, ferruginous soft sandstone; ghosts of limonite ooliths throughout; very	

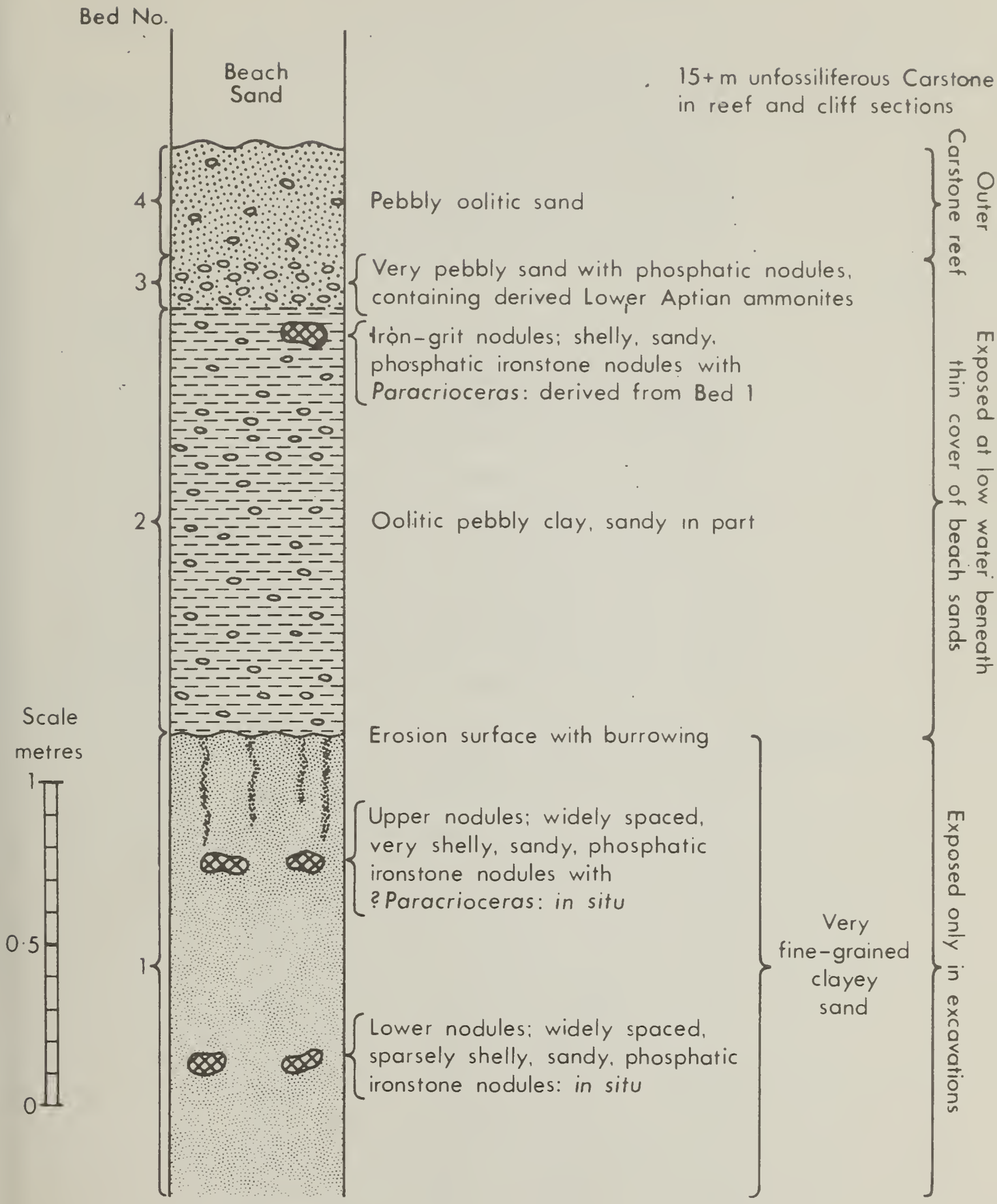

Fig. 1. Generalized vertical section through the beds exposed in the Hunstanton beach excavation.

rare phosphatic nodules as below; passage at base into 0.03m

Bed (3): Sandstone, as above but very pebbly and including dark brown generally well rounded phosphatic nodules (up to 0.1m across but mostly 0.02 to 0.03m), some with worn specimens of Lower Aptian ammonites, including Cheloniceras, Dufrenoyia, Prodeshayesites, and Tropaeum: larger unfossiliferous phosphatic nodules (up to 0.12m across) also occur, mostly of burrow fill shape. In some sections phosphatic nodules are extremely rare, in others they occur in clusters; Bed (3) is locally less pebbly and indistinguishable from Bed (4). Ferruginous seepage at base 0.15 to 0.20m

? CARSTONE: Bed (2): Dark grey and greenish grey oolitic (chamosite, largely oxidised to limonite) pebbly clay, sandy in part, intensely burrow-mottled and varying both laterally and vertically in composition with pebbles and ooliths concentrated in bands generally 0.15 to 0.20m thick; pebbles (mostly iron-stained quartz) lithologically identical to those of Beds (3) and (4). Large well rounded nodules of very fossiliferous sandy phosphatic ironstone (the 'iron-grit' nodules of Keeping 1883, p.33) were collected from near the top of this bed in the 1930s (e.g. British Museum(Natural History) specimen Nos. C35512 and C35238).

Thickness variable; very irregular sharp base with burrow fills of fine and medium-grained greenish yellow sand (Carstone lithology) extending down to 0.5m below the junction; irregularities of up to 0.15m observed in 2m length of junction 1.00 to 1.50m

ROACH: Bed (1): Pale and medium grey intensely burrow-mottled sands and very fine-grained clayey sands; traces of cross-bedding and burrow-mottling. Fragments of coalified wood scattered throughout. Lines of nodules occur at 0.4m and 1.0m below the top of the bed. The upper nodules are very widely spaced: only two were obtained from about 6 metres of trenching. These nodules are up to 0.2m across, rounded, irregular and burrow fill shapes, composed of dark brown phosphatic ironstone containing many sand grains, and crowded with moulds of small bivalves and rarer brachiopods, gastropods and ammonites. Bits of coalified wood are also common. Their lithology and fauna is identical to that of the 'iron-grit' nodules from Bed (2); they differ only from the latter in that they are less well-rounded and, on their outer surfaces, they have retained traces of the cross-bedding and burrow- mottling of the sands. The lower nodules in Bed (1) are probably only slightly less widely spaced than the upper nodules: their matrix and occurrence is similar to that of the

upper nodules, but they are much less fossiliferous. Small pyrite concretions occur in association with them. Similar faunas, including ?Paracrioceras , occur in the nodules at both levels. Base of bed not seen. 1.5m

Bed (1) is clearly the source of the 'iron-grit' nodules of Bed (2); the fauna of these nodules is part of the indigenous fauna of the Bed (1) sands. The fauna has been described by Casey (1961, p. 571) as including 'Barremian ammonites of the genus Paracrioceras'. The fauna from the upper nodules of Bed (1) from the 1973 excavation has been described by Morter (1975, p.) as being similar to that of part of the Roach of Lincolnshire and probably of Middle Barremian age.

A similar lithological sequence to the above, but without nodule bed or macrofauna,was recorded in the Institute's Hunstanton Borehole (TF 68574078). In this borehole, the sands correlated with Bed (1) of the beach excavations (Gallois 1973, Fig.2) form part of a complex sequence of sands, clays and pebbly oolitic clays which can be lithologically matched with the Roach of Lincolnshire. The faunal evidence form the new excavations confirms this correlation.

The new excavations have also provided additional information about the variable nature of Bed (2) and about its erosional contact on Bed (1). It now seems very likely that Bed (2) is a basal clayey bed of the Carstone, possibly of limited local extent. Elsewhere in Norfolk the basal beds of the Carstone have rarely been exposed and their lithology may well be variable. At present, exposures at Leziate Sand Pits (TF 684194) show the basal beds to be of typical Carstone lithology (ferruginous sandstone) whilst those at Blackborough End (TF 677144) are of soft uncemented fine-grained sands.

If Bed (2) is part of the Carstone then the possibility exists that any future excavations might yield indigenous ammonites, and thereby prove beyond all doubt the age of the Carstone at Hunstanton.

Acknowledgements

Once again the success of the field meeting was due entirely to the enthusiasm and generosity of Mr. Hamon Le Strange of Hunstanton, who suggested, financed and organised the excavations. In addition, his daily searches of the tide-sorted spoil from the excavations yielded much more faunal material than could be collected during the field excursions.

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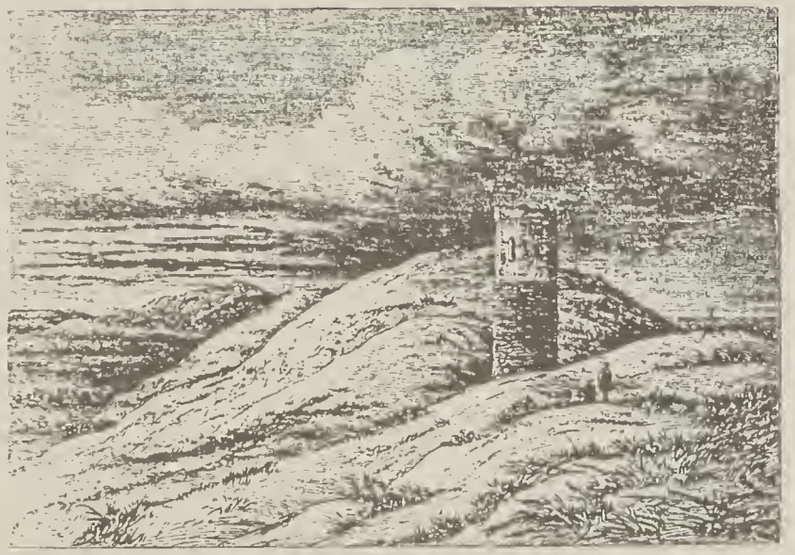
Received August 1974

which are always moving inland, had considerably altered their position in reference to the tower, which after the storm of 1862 was seen as represented in fig. 44, on the sea-side, the waves having washed the foundations of the edifice.* The level of the base of the tower, and of the ruins of the nave and chancel of the church (see fig. 44) has

Fig. 43.



Tower of the buried Church of Eccles, Norfolk, A.D. 1839.

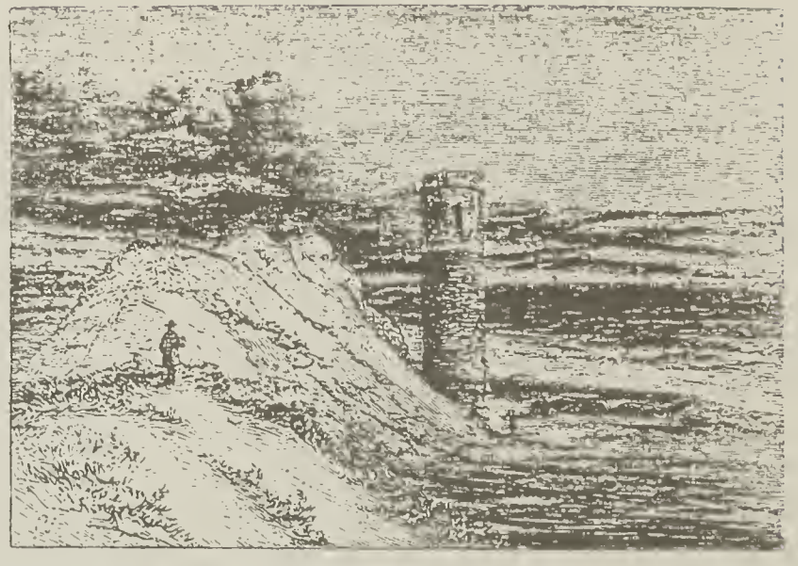
The inland slope of the hills of blown sand is shown in this view, with the lighthouse of Hasborough, N.W. of the tower, in the distance.

now such a relation to high-water mark, that Mr. King naturally suggests that there must have been a subsidence of this part of the coast since the church was built. The precise date of its erection is unknown, but the upper or octagonal part of the tower is supposed to date from the 16th century, and this addition would not have been made at that period had the site been considered as in danger from the encroachments of the sea.†

Observations on the level of the foundations of buildings

now within reach of the tide may hereafter lead us to an exact estimate of a change of level if there be one in progress, although antecedently to experience, we might have anticipated that a wasting coast was less favourable than any other for ascertaining whether the land was rising, sinking,

Fig. 44.



Eccles Tower as it appeared after the storm of November 1862, from a drawing by Rev. S. W. King, taken from nearly the same position as fig. 43.

or stationary. As the tide rises eight feet at Lowestoff, and sixteen at Cromer, it becomes a question whether in the course of four or five centuries its mean level at any given point on this eastern coast may vary sufficiently to explain the present position of the ruined church at Eccles relatively to high-water mark, but I am not aware that we have any recorded data for confirming or invalidating such an hypothesis.

(From Lyell's 'Principles of Geology' 1867)

28 "Lyelliana"

Bull. geol. Soc. Norfolk., 27, 29 - 32 (April 1975)

A BARREMIAN FAUNA FROM EXCAVATIONS AT HUNSTANTON BEACH

A.A. MORTER*

The fauna from some sandy phosphatic ironstone nodules (the upper line of nodules of Bed 1 of Gallois 1975, Fig. 1), obtained from excavations at Hunstanton beach, is described. The fossils are preserved largely in the form of external moulds and steinkerns, with some original shell material present. Much of the material is fairly well preserved, although in some cases replacement of the shell has resulted in the loss of ornament on the exterior shell moulds.

The fauna is varied and includes brachiopods, scaphopods, gastropods, bivalves, and ammonites, the bivalves being by far the most abundant, both in number and variety. Wood fragments are also common.

The following fauna was recorded: specimens have been registered in the Institute of Geological Sciences Collections under Nos. Zr 9731 to 9770.

Brachiopoda	*Rhynchonella parkhillensis* Owen and Thurrell
	terebratelloid
Scaphopoda	*Antalis* sp.
Gastropoda	*Tressarolax* sp.
	cf. '*Trochus*' *stillei* Wollemann
	small gastropods indet.
Bivalvia	*Acesta* aff. *longa* (F.A. Roemer): ?sp. nov. (mytiliform)
	'*Anomia*' sp.: probably *Paranomia laevigata* (J de C Sowerby)
	Astarte sp.

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Chlamys cf. aptiensis (d'Orbigny) [Syn., Chlamys robinaldina Auctt]
Entolium sp.
Freiastarte cf. subcostata (d'Orbigny)
Limatula cf. tombeckiana (d'Orbigny)
Mulletia mulleti (Deshayes)
'Nuculana' sp.
Oxytoma pectinatum (J de C Sowerby)
Parmicorbula striatula (J de C Sowerby)
Resatrix sp.
Teredolites in wood with contained Terebrimya sp.
Thetis minor J de C Sowerby

Cephalopoda ?Paracrioceras sp.
non-heteromorph ammonite, fragment only
?desmoceratid ammonite, early whorls only

Many of the forms are long ranging and it is difficult to assign a precise age to the fauna. The most comparable fauna is that of the lower parts of the Roach of Lincolnshire, generally accepted as Barremian in age. Several of the bivalves have Aptian affinities; but such affinities are typical of Middle and Upper Barremian faunas in general, eg. the faunas described by Gillet (1921) from Wassy (Haute Marne) in the eastern part of the Paris Basin. Attention can also be drawn to the marked similarities in lithologies at the level in the Barremian between such widely separated outcrops as Wassy, Salzgitter in West Germany (Michael 1967) and Hunstanton.

The beach nodules, which are characterised by abundant Parmicorbula striatula, were not represented in the stratigraphically equivalent, sparsely fossiliferous clayey sands of the Hunstanton Borehole (Gallois 1973, Fig.2). However, the nodules are faunally similar

to a lower stratigraphical level in the Hunstanton Borehole where this species also occurs in abundance. This lower level is presumed to correlate with the Roach stone of the Lincolnshire succession as defined by Swinnerton (1935). The occurrence of Rhynchonella parkhillensis in the nodules, only previously recorded from the Roach Stone of Lincolnshire (Owen & Thurrell 1968), supports a correlation within the Roach sequence.

The absence in the nodules of Corbula isocardiaeformis indicates on the basis of unpublished borehole information, a level younger than the Snettisham Clay and its lateral equivalent the Upper Tealby Clay, which has been dated by Kaye and Barker (1966) on ostracod evidence, and on belemnite evidence by Swinnerton (1935) and Rawson (1972) as Lower Barremian.

The ammonites in the nodules are all incomplete, but the occurrence of ?Paracrioceras which ranges in Germany from the uppermost Hauterivian to the top Middle Barremian (Michael 1967, p. 137) is not at variance with a Middle Barremian age, i.e. post proven Lower Barremian, for the nodule fauna.

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FIELD MEETING TO BRAMERTON, NEAR NORWICH, 14-15 SEPTEMBER 1974.

P.G. CAMBRIDGE*

Introduction

This was the first meeting of the Society to take place on more than one day, the object being to excavate an important geological site. Blake's Pit, Bramerton, (TG 301063) was chosen for several reasons, not the least of which was the fact that the incoherent sands are fairly easy to excavate! It was hoped to produce a measureable section, which would remain accessible for some time, and above all to expose the base of the section. The Crag at this point is known to rest on Chalk, but the exact height above river level and the precise zone of the Chalk were unknown. It was assumed that this was the *Scrobicularia* Pit of early authors, but since this species was not found in the exposed upper beds in the pit, there was some doubt. In all twenty-two members and friends took part over the two days, and almost all the aims of the 'dig' were achieved. Samples of the Chalk were collected, but unfortunately no fossils were found which would establish the age of the Chalk at this point.

History of the Section

Mention has been made of 'Blake's Pit', or the *Scrobicularia* Pit in several of the old memoirs. Shells were stated to occur in patches throughout the section and *Scrobicularia plana* was common, but no section was given. The Common Pit, nearby, was described in some detail and was subsequently re-excavated and described by Funnell (1961) who studied the Foraminifera and divided the Norwich Crag at Bramerton into three horizons. The Crag of the area has been considered typical of the

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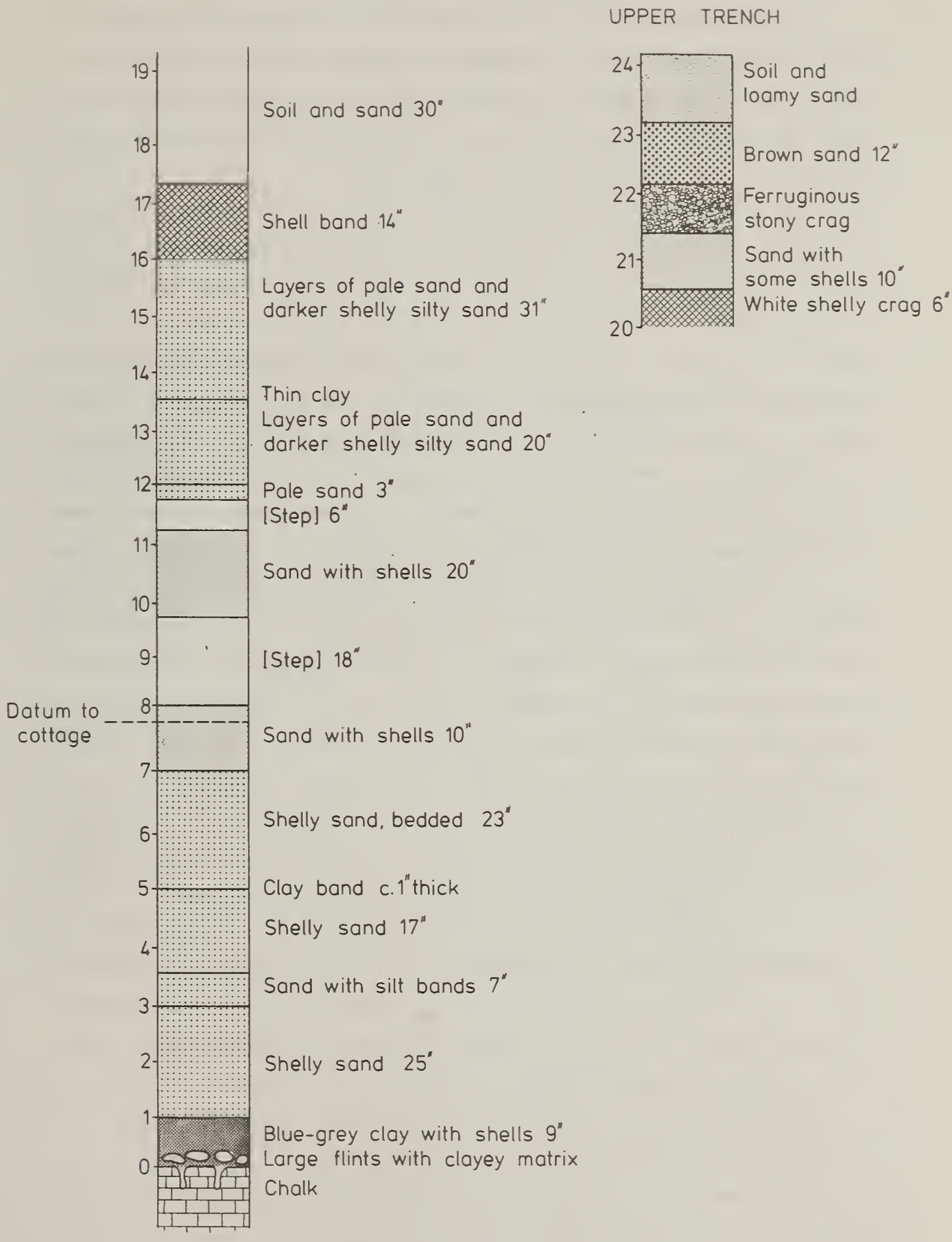
'Norwich Crag' facies of the Icenian of F.W. Harmer, and in general is recorded as an Upper and Lower Shell Bed, with more or less unfossiliferous sands between, the whole resting on a Stone Bed on the surface of the Chalk. So far the Crag at Bramerton has not been fitted into the series of palynological zones established by West(1961) and others , and it is hoped that clay samples taken during the 1974 meeting will yield a useful pollen series.

The pit stands close to the river and truncates a ridge between two of the small dry valleys which indent the river valley sides at frequent intervals in this vicinity.

Description of the Section (Fig. 1)

No fossils were noted in the Chalk at the base, but a large flint was excavated. The surface of the Chalk has minor irregularities and is stained slightly brownish by iron oxide. It is penetrated by numerous small, rather irregular cavities or fissures, usually tapering downwards, often turning at right angles, sometimes expanding or branching. At the surface the fissures are marked by rather irregular hollows, and the average penetration into the Chalk is about 70mm. Small, dark-brown nodules occur in the cavities in a matrix of the overlying Crag, and these may be phosphatic. One or two typical flask-shaped burrows of bivalves were seen (probably *Zirphaea* sp).

The Stone Bed consists of medium sized flints, the flatter examples being horizontally bedded; many of the flints are heavily corroded by subaerial weathering, and showing no signs of rounding of sharp edges or chatter marks. The matrix is a greenish, silty clay with shell fragments, and the flints are stained a dark, greenish colour. Apart from flint the only other constituents were a few of the small dark nodules (10mm) and some larger ironstone or phosphatic nodules with empty crypts



SECTION: BLAKE'S PIT, BRAMERTON
FIG. 1

of Pholad shells penetrating from all directions.

The Stone Bed is followed by a series of sands with shells and shell fragments with occasional thin seams of clay. These sands are noticeably more shelly towards the base while near the upper part there are beds without any visible shell remains.

At the top of the section (the only part visible for many years) is a bed of extremely shelly sand, showing up as a light-coloured band, resting on non-shelly sand. In this Upper Shell Bed the valves of lamellibranchs lie in layers with the convex surface uppermost. Macoma, Mya, Spisula and Cardium are the most common species. The gastropods Nucella and Littorina are abundant. Most of the common shells are unworn and occur in all stages of growth, but usually do not have an epifauna, although marks of polyzoans are sometimes seen on the shells and detached valves of barnacles are abundant. All the shells are partially decalcified and tend to be fragile. Small tabular fragments of black peaty material are common, the sand is coarser and occasional pebbles occur. The upper part of this Shell Bed shows somewhat apparent reworking, the shells occurring in patches and being more worn, the colour darker and pebbles forming small bands. Fragments of bones are commoner in the upper pebbly patches.

The Upper Shell Bed is followed by brown sands and ferruginous stony beds similar to those seen elsewhere above the Crag. At this point the section reached the brow of the hill and further sections would have entailed a new trench among well established trees.

Since the section is in the form of two narrow trenches lateral variation is not known, and because of the considerable lateral variation, which is a usual feature of the Icenian Beds, the section examined can only be assumed to be typical. In general the section agrees with that given by Funnell (1961) for the Bramerton Common pit, with the Upper Shell Bed of Blake's Pit

equating with the shell bed at the top of horizon BII. Unfortunately the foraminiferal horizons have not been established for Blake's Pit and the mollusca are not well recorded at Bramerton Common. However Norton (1967) has recorded '*Littorina littorea* var. *carinata*' from BII and this further suggests a correlation between the two shell beds. Special importance is attributed to this Upper Shell Bed by the present author because of unusual features in the fauna and its possible use as a stratigraphical marker in the area.

Interpretation of the Section

Since it has not yet been possible to study all the material collected at Blake's Pit in detail some of the following can only be tentative suggestions. However, the author has examined a considerable bulk of material from the upper part of the pit. What can be called the 'background fauna' of the Icenian is very similar in most sections, and indeed, apart from the extinct forms, bears considerable resemblance to the modern fauna of the southern North Sea. It is the rarer forms which probably give more information on conditions during the Icenian. Non-marine shells occur in many of the Icenian exposures and when eventually studied should give some insight into conditions on the nearby terrestrial surface; they will not be subject to the vagaries of marine currents as are the marine molluscs. However, sampling of small quantities of material would probably not produce any of these important forms.

The unconformity between the Chalk and the Crag represents a gap of at least seventy million years. It seems likely that during at least part of the Tertiary the area was dry land. The shape and condition of the flints in the Stone Bed at Bramerton suggest a long period of weathering and erosion of the Chalk surface. I have been unable to match the small irregular fissures (Fig.2) in the Chalk surface with any marine organisms. Further,

the large pholad borings, cut through the fissures and must therefore be subsequent. It is suggested that the fissures were a terrestrial solution feature, perhaps formed by roots of plants. During the Icenian transgression the earlier stages may have been the formation of a series of drowned valleys, rather like those at present seen in Suffolk and Essex, with small clear rivers or streams originally occupying the valleys. The fine basal material, the lack of wear on the eroded flints, and the presence of examples of Mytilus and Yoldia with joined valves in the basal bed point to quiet deposition.

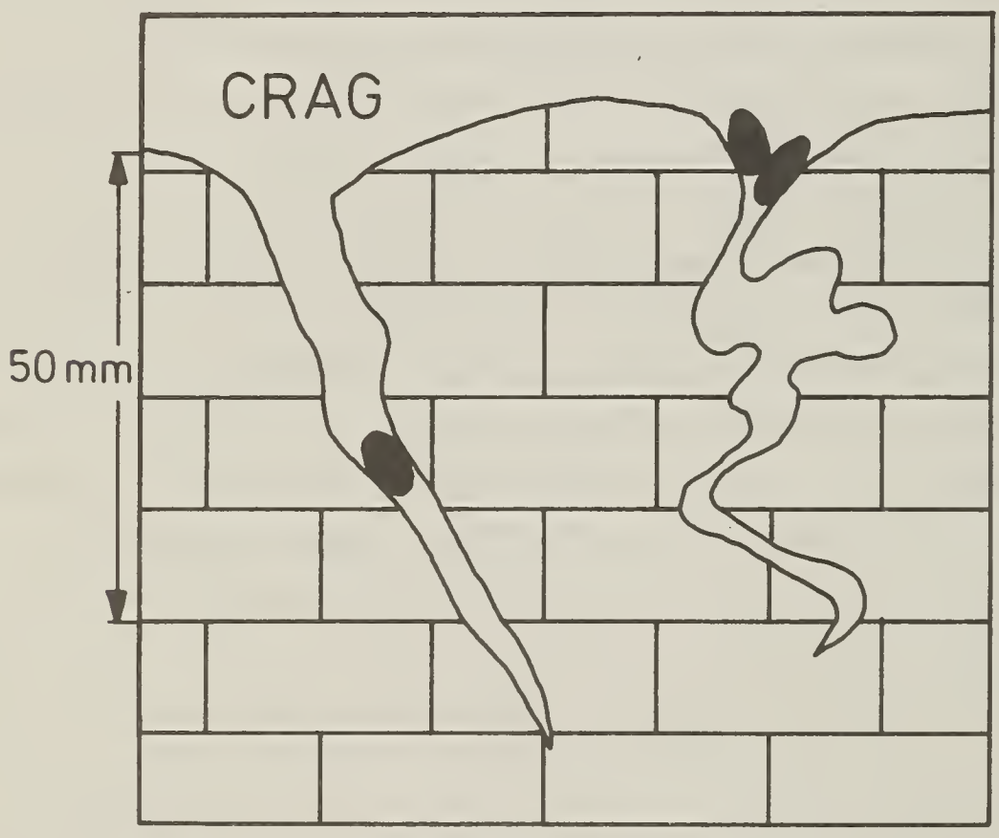


Fig. 2 Diagram of fissures in the chalk surface

The abundance of mammalian remains lying on the Stone Bed in the Norwich area, coupled with their fragmentary nature and the mineralisation of many, but not all, of the bones, suggest their derivation from valley gravels during the marine transgression, when some may have already been mineralised. Finally the scattered teeth and bones of small mammals (mice and voles mainly), and the presence of a fairly large non-marine fauna, would be consistent with long estuaries with side streams, rather than open bays or coastline.

The Shelly Sands above the Stone Bed have only been lightly sampled, but the fauna contains many small marine gastropods and apart from Neptunea large shells are not abundant. Non-marine shells are by no means rare, and in a sample of about 10 kg about twenty pulmonates were found, including: the possibly estuarine Ellobium, the fresh-water Planorbis and Lymnaea, the land snail Vallonia and at least two other distinct forms of land snails. The presence of thin seams of clay, small changes in grain size, and the absence of shells in some of the sands may be due to changes in current strength, although no actual examples of oblique current bedding were noted.

A more obvious change in conditions is immediately apparent in the Upper Shell Bed. The presence of larger pebbles, the convex uppermost orientation if bivalves, etc. point to stronger currents. Yet clearly some of the material cannot have travelled very far - the fine crenulations on Nucella are frequently quite unworn, and juveniles only 2 to 3mm long occur mixed with large adults of the same species. It is possible that the large bivalves were transported to form shell banks on which the active gastropods such as Nucella and Littorina lived. The very thin shells of the brachiopod Hemithyris psittacea may have been attached to heavier shell fragments or pebbles. Many of the commoner shells in this bed are abundant on tidal flats and in estuaries today; many are intertidal.

Perhaps the most unusual feature of this bed is the presence of monstrosities and extreme variations in some of the species. No common factor seems to be apparent. The species affected include the carnivore Nucella, the scavenger Neptunea and the algae browsing Littorina. The distortions take two forms The first are monstrosities with no immediately apparent cause - compressed, elongated, scalariform, and heavily keeled forms; the second are usually caused by mechanical damage to the shell or to the presence of barnacles growing on the shell close to the suture, sometimes resulting in complete and random dislocation of the whorls, However, it should be noted that even in the case where barnacles are a causative factor, Balanus spp. and Littorina spp. commonly live together at the present day, and such Littorinas seem capable of dealing with such unwanted additions without distortion. It would appear that some other factor reduced the Littorina's ability to deal with the presence of barnacle larvae, and that the barnacles are a secondary factor in this case. It is curious since at the present day Littorina is a genus singularly free from monstrosities. The remainder of the molluscan fauna, which is fairly large, does not show any such tendency to acute variation. The area in which these forms occur is quite small, having been noted only at Bramerton, Postwick Grove and what appears to be reworked Crag in the Glacial Series at the Sewage Works, Whitlingham. It also seems probable that the monstrosities are confined to the the Upper Shell Bed. Distorted coiling of foraminifera has been recorded by Funnell (1961) from Bramerton and also occurs in Icenian at Thorpe Aldringham in Suffolk. Grossly enlarged fishbones, referred to "Platax", are fairly common in the Upper Shell Bed but are also found at other localities in the Icenian. It is notable that they usually occur in beds which contain many small bone fragments and pebbles, and generally in 'shell bands'. The Upper Shell Bed at Bramerton has also yielded examples of Viviparus medius, Pisidium and a number of land shells, as well as vole

teeth and remains of other small mammals and fish, especially in the uppermost part of the shell bed which has a reworked appearance. The rather more pebbly bands at the top of the shell bed have also yielded a few derivative fossils. The presence of flint moulds of belemnite alveoli, and derived Chalk fossils is easily explained. Fragments of Oxfordian ammonites and a piece of crinoidal limestone less easily so. Unlike the Red Crag which contains a large derived fauna from the Eocene, derived Tertiary fossils seem unknown in the Norwich Crag, although the Crag sands transgress over the London Clay from the east. Probably this is due to the Icenian area being more sheltered. Two fragments of the polyzoan Metrarabdotos moniliferum were found in the sample from the lower shelly sands of Blake's pit and since the species does not seem to be known later than the Pliocene, except as a derivative, these specimens may have come from earlier Crags, especially as they are only a few millimetres long.

As elsewhere in the Norwich area, the sandy, shelly Norwich Crag is succeeded by a pebbly, ferruginous series, and decalcified sands. It is possible these may have been originally fossiliferous and subsequently suffered decalcification, reduction of the contained iron, etc., or they may represent high energy shallow water or beach conditions, or possibly have been reworked during the regressive stage of the Icenian cycle. In none of the cases can the shore line have been far to the west, probably somewhere in the region of the present 150 foot contour.

The question of the temperature changes in the Icenian is a difficult one. The foraminiferal sequence of Bramerton Common has been interpreted as a steady cooling ending in very cold conditions. Some of the marine shells of the Upper Shell Bed are at present indicative of high latitudes, such as Hemithyris psittacea, Boreoscala, Macoma calcarea; while others, such as

Calyptraea chinensis are at present more southern. Many bivalves show great tolerance to temperature changes; for example Arctica islandica occurs in the warm Miocene and Pliocene, is abundant in most of the Crag beds and equally abundant in the cold Clyde Beds. The non-marine shells would seem to indicate a temperate land surface. A clay sample from the upper part of Blake's pit contained some pollen, not too well preserved, in which Pinus predominated, suggesting a cooler phase, probably from the BII horizon, but the sample was insufficient to make any definite statement. It is hoped that a study of the pollen and the mollusca of the lower part of the section will eventually yield further information.

Palaeontology

Faunal lists have been published in the literature (Taylor 1871, etc., Reid 1890, Woodward 1881, etc.) for the area, though much of the nomenclature is now out of date. Only certain forms of special interest are here mentioned.

Littorina spp. Examples in all stages of growth are abundant, often with the colour bands well-preserved. Both L. littorea and L. rudis (s.l.) are present, but since the taxonomic status of the modern species is in doubt it was felt best to group the fossil examples together. The variation in the group was checked by passing a 100 kg sample from the Upper Shell Bed through a 1/4 inch sieve. Juveniles were thus lost. All adults were examined for variation and the following figures obtained:

Normal shells		556 examples
Minor variations	79	
Gross monstrosities	90	
Totals	169 (23%)	556 (77%)

In the lower shelly sands 'rudis' seems more common than 'littorea' and no monstrosities have been noted so far.

Nucella lapillus (Linné). Both adults and juveniles occur and examples are at least twice as abundant as

Littorina . Most are a thin shelled form, with occasional slight distortion of the whorls, and large apertures, and show very little sign of wear. Low spired, thick, small examples are rare and usually worn; a few are denticulate within the mouth. The variation seems to fall within that of the modern form. Some examples have the whorls slightly distorted by juvenile barnacles. Monstrosities occur, e.g. monstrosity angulata Woodward, but much more rarely than among the Littorina specimens. Anyone interested in these monstrosities should see the figures in Wood (1848-82) and Harmer (1914-25). Harmer's figure of Neptunea despecta var. pumilio is actually a monstrous Nucella lapillus.

Neptunea spp. Several species are found in the Crags. This genus entered the North Sea in late Pliocene times from the Northern Pacific. The first forms were usually strongly carinate and were mistakenly referred to N. despecta by Harmer. Later, in the early Pleistocene, a smoother form appeared and was referred to N. antiqua. Both forms continue throughout the Crags and were difficult to separate owing to the presence of intermediate forms. Strauch (1972) referred both forms to a new species N. lyratodespecta which was strongly ribbed, and the smoother variety to a subspecies striata (Sowerby). Some modern conchologists prefer to consider both as forms of N. antiqua. At Blake's pit the Neptunea specimens in the lower part are finely ribbed and referred to N. lyratodespecta striata. The examples in the Upper Shell Bed are mostly those figured by Harmer as var. curtispira and var. decemcostata (not Say). Both would appear to be extreme variations or monstrosities of N. lyratodespecta. A second species N. contraria, also reached the North Sea in Upper Pliocene times and is abundant in the Scaldisian and the Red Crag but rare in the Icenian. An example was found in the Upper Shell Bed during the dig, the example lacking the typical ribbing of the species, probably due to wear.

Fish remains. These are common in the Upper Shell Bed, including indeterminate vertebrae, dermal ossicles of *Raja clavata*, and vertebrae and bones refered by Agassiz to *Platax woodwardii*, on account of the swollen appearance of the bones (hyperosteosis). The Platicidae, a group of recent Indo-Pacific fishes, show indiscriminate swellings in the bones, apparently not of pathological nature. However, it seems somewhat unlikely that a tropical fish genus should appear in the North Sea during the Icenian only. Study of the bones suggested that they may not all belong to the same species. Certain of the bones have a different colour and appearance; these particular bones are also found in deposits in the West Schelde, Netherlands, but with no sign of the elongate vertebrae and 'butterfly bones' which were included in Agassiz' species. A comparison with modern North Sea fishes showed a close resemblance to the cleithrum, a bone from the skull of a gadoid fish. Since large otoliths, referable to the cod, *Gadus morrhua*, are occasionally found in the Icenian, it seems probable that the bones mentioned belong to cod. The remaining elongate vertebrae and 'butterfly bones' are left in '*Platax' woodwardi* for the time-being until a better indentity can be established. It is interesting that distorted fish bones occur in the Upper Shell Bed together with various molluscan monstrosities, but the combination is probably accidental since these bones occur in a number of localities (Covehithe Warren, Easton Bavents, Thorpe Aldringham, Broome, Bramerton, Whitlingham, Thorpe, Weybourne) although they only appear at certain horizons, usually associated with shell beds, and coarse material.

Notes on the Section (Fig. 1)

A narrow trench (c.1 metre) was dug on the left hand side of the pit from the top of the section to a short distance below the top of the Chalk. A second section, a little to the west of the first, was measured and cleared

to a depth of six feet. A datum point was made, to the eaves of a near-by cottage, and all measurements referred to this. At a later date it is hoped to survey an absolute level above OD. The Upper Shell Bed was not at the same absolute level in the two trenches and appears to follow the curve of the top of the ridge. Whether this is due to irregularities in the Shell Bed or to cambering on the ridge side is not known.

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FOSSIL ICE-WEDGE POLYGONS AT CORTON, SUFFOLK

K. GARDNER* and R.G. WEST[1]

In January 1971 a scour at Corton Cliffs (Fig. 1) re-exposed the Cromer Forest Bed Series in the upper part of the beach. The section here is well-known through the cliff-section and description of J.H. Blake (1884, 1890), but exposures have been rare since then, and indeed are unlikely to occur again, as the recently-built sea defences have led to a permanent build-up of the beach.

The sequence at the cliff-base is as follows:

Brown boulder clay (Lower Boulder Clay, North Sea Drift, Norwich Brickearth)

Cromer Forest Bed Series:
- Laminated grey silt and sand up to 2 m thickness
- Wood peat and coarse detritus mud up to 0.25 m thickness
- Grey-blue clay (Rootlet Bed)

The Rootlet Bed is a marsh clay, and the wood peat and detritus mud reflect a higher fresh-water level with rich organic deposition. A marine transgression followed, depositing inorganic tidal sediments. Finally the area was overrun with the ice which deposited the boulder clay. The palaeontological content of the Forest Bed Series at Corton indicates a correlation of the three horizons to a period within the Cromerian temperate stage (type site at West Runton).

The scour in 1971 revealed a plan view of ice-wedge casts. They are mapped in Figure 3, with an example in

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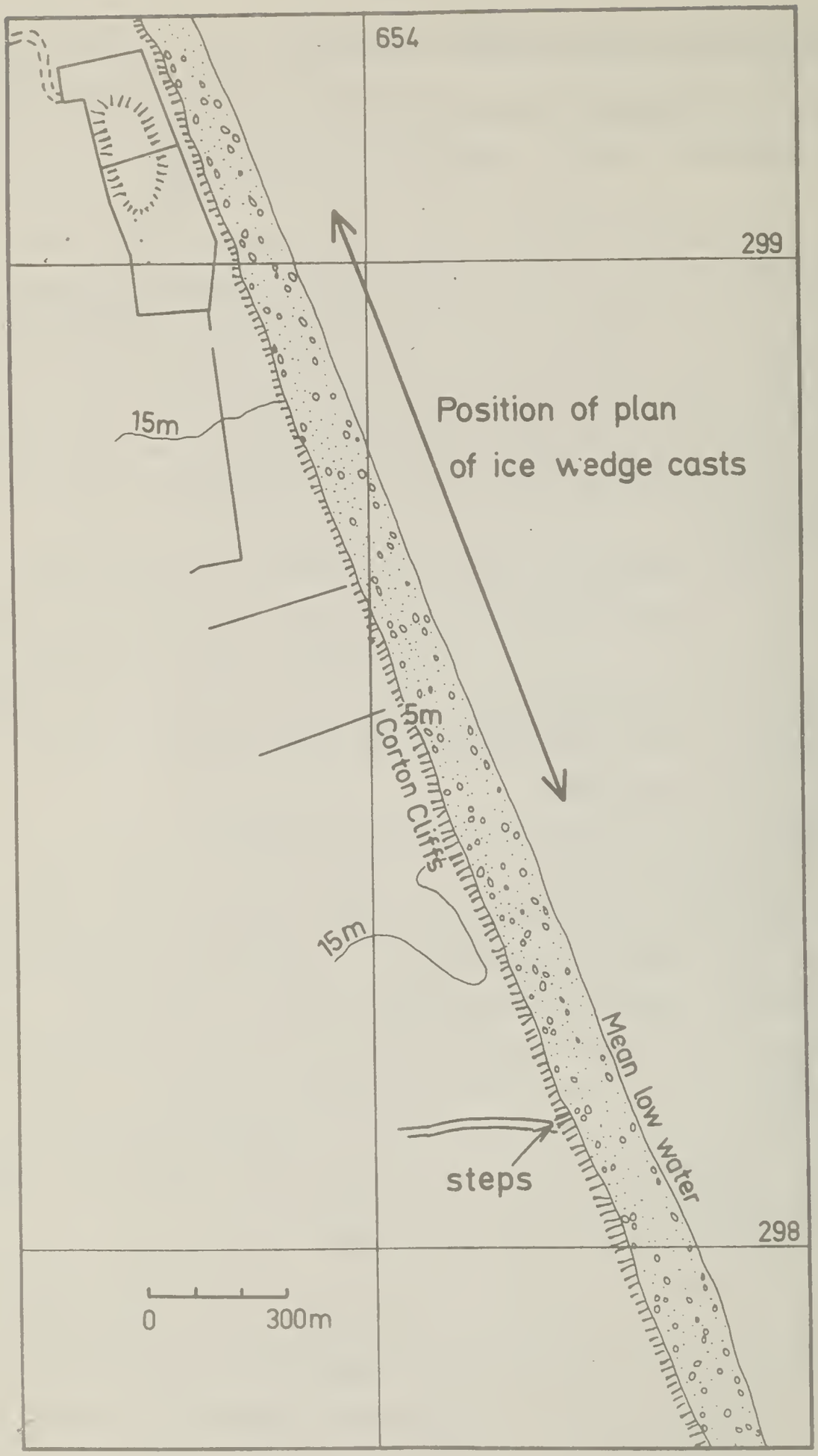

Fig. 1 Map of Corton Cliffs, showing position of polygon exposure.

Figure 4. Figure 3 also shows the position of two small basin-like features which may have originated by the collapse of ground-ice.

The ice-wedge casts penetrate the Rootlet Bed to depths of up to 1 metre, and are rendered conspicuous by the ferruginous oxidation of the clay along their flanks. The oxidation is at a maximum along the centre line of the wedges and merges outwards in each direction, with varying degrees of abruptness, to the unweathered grey clay. Figure 2 shows two sections, five metres apart along the most northerly wedge observed, drawn when the wedges were exposed in 1961.

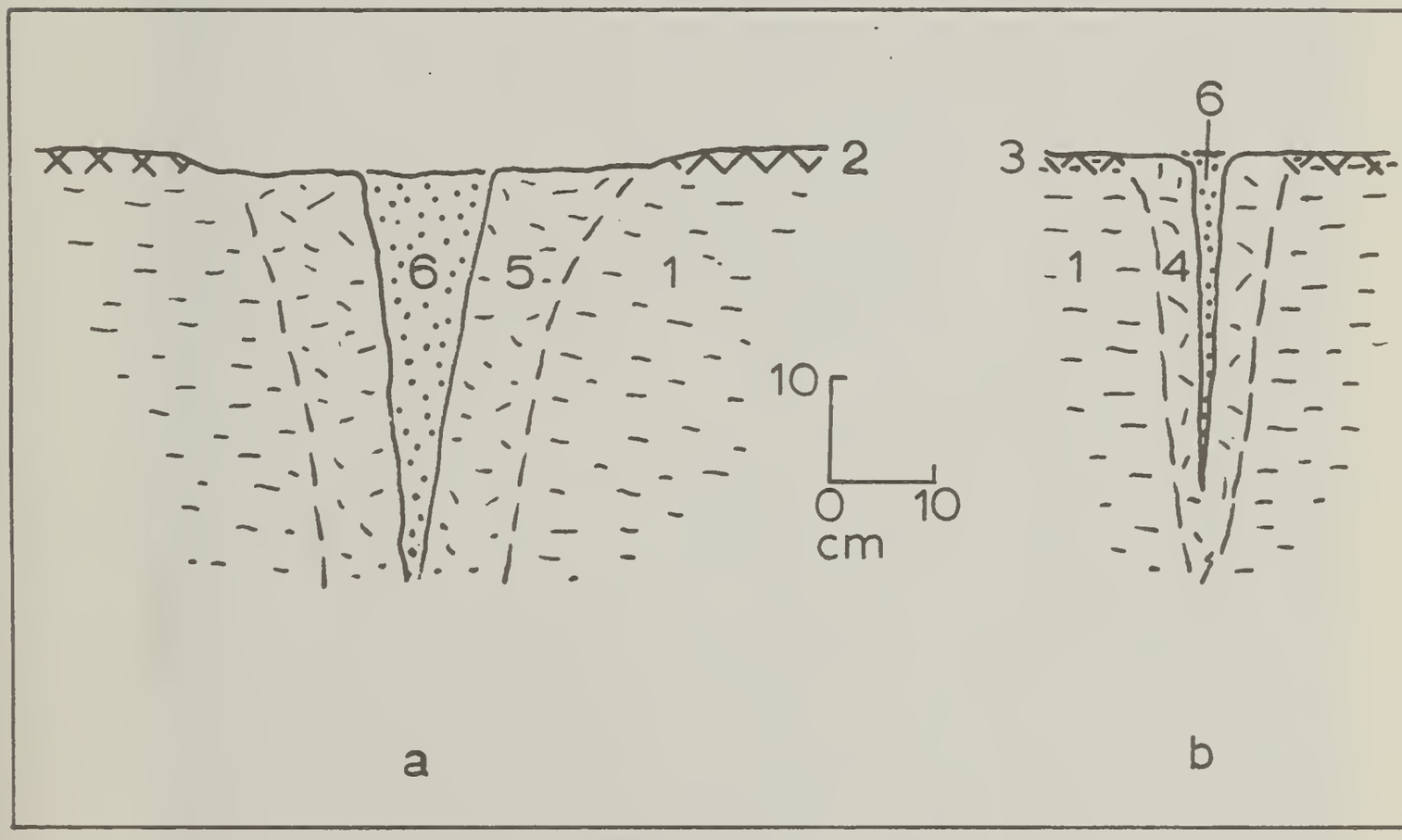

Fig. 2 Sketches of sections across an ice-wedge cast (1961): (a) at foot of cliff; (b) 5 m east of foot of cliff. 1. grey-glue clay of Rootlet Bed; 2. organic mud; 3. muddy clay; 4. yellow-brown oxidised clay, sharp transition to 1; 5. crumbly, weathered yellow clay, merging gradually into 1; 6. coarse ferruginous sand.

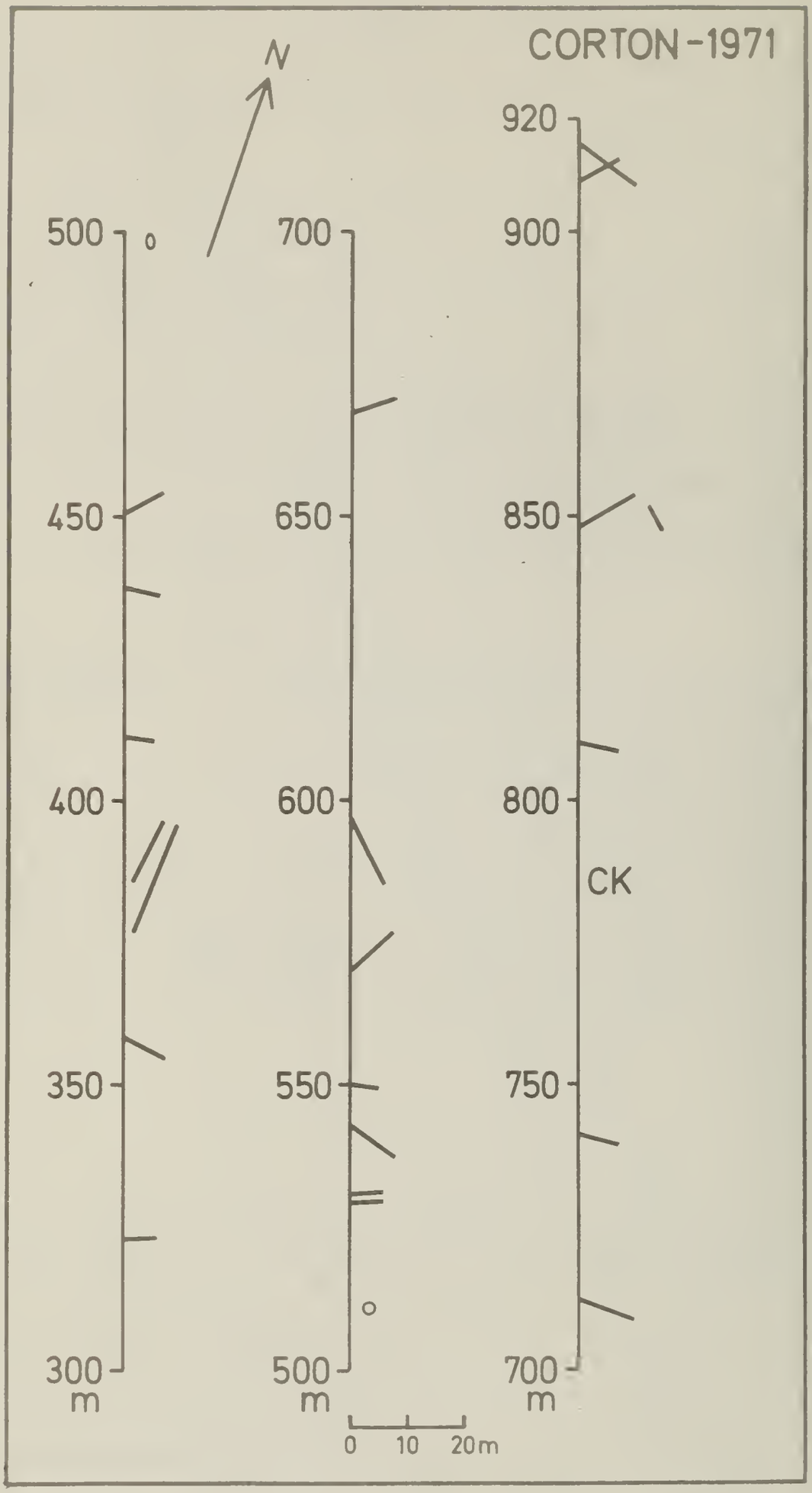

Fig. 3. Plan of ice-wedge casts. Distances in metres N of stair down cliffs opposite St. Bartholomew's Church. CK indicates positions of section under palaeobotanical study.

Fig. 4 View to seawards of ice-wedge cast penetrating peat and Rootlet Bed.

Being an unconsolidated clay, the Rootlet Bed shows no regular system of jointing, but only small, starch-like fracture cracks an inch or so apart. There is no trace of ferruginous weathering along these minor cracks or over the upper surface of the clay generally. Oxidation similar to that along the wedges does, however, occur around the two small basins.

An examination of Blake's (1884) horizontal section shows that he drew structures interpretable as ice-wedge casts at exactly the same position along the cliffs as those seen in 1971, although he did not interpret them as such. On the horizontal section, the wedges are below the boulder clay and they penetrate the total thickness of the tidal sediments, the peat and the Rootlet Bed. In 1971 the upper part of the wedges could not be seen, but they were observed to penetrate the tidal silts, the peat and the Rootlet Bed. The polygons evidently formed subsequent to the Cromerian, during the Anglian cold stage but before the deposition of the boulder clay. They probably belong to the same permafrost episode that produced wedges immediately below the North Sea Drift at West Runton and at Mundesley. They cannot be correlated with the ice-wedge polygon system observed immediately above the Pastonian tidal silts at West Runton (West 1968).

The extent and spacing of the ice wedge casts shows that a true large-scale arctic polygon system developed in early Anglian times, before the arrival of Anglian ice, indicating very low mean temperatures (below -6°C) at the time. The 1971 observations also testify to the powers of observations of J.H. Blake, even though his correlations of the pre-glacial Pleistocene of the coastal area were challenged by Reid and Whitaker (in Blake 1890).

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ECCLES STEEPLE, NORFOLK, BEFORE THE STORM OF OCTOBER, 1862.

- an intermediate stage between Lyell's views of Eccles tower in 1839 and <u>after</u> the storm of November 1862.

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THE CONTORTED DRIFT OF NORTH NORFOLK.

P.H. BANHAM*

Introduction

This is a brief account of a lecture delivered to the Society on 18 November 1974. Fuller accounts of the evidence and ideas touched on here will be available shortly (Banham 1975, and in a revised version of "The Geology of Norfolk").

The Contorted Drift is best developed and exposed in coastal cliffs between Mundesley and Weybourne. The complex fold and thrust-raft structures found there in the glacial and glacifluvial deposits have been generally attributed to deformation by ice (Reid 1882, Slater 1926, Dhonau & Dhonau 1963, Banham 1968). This being so, it may be helpful to review the nature of glacitectonic structures elsewhere before considering the Contorted Drift of Norfolk.

Glacitectonic structures in Europe and North America

Four main types of geomorphological site of glacitectonic deformation may be recognized, although it is accepted that these are essentially points in a spectrum.

1. Veluwe Type (valley sides) In the Veluwe district of Holland superficial thrusts are developed in soft sediments where these had previously been cut by generally northward flowing rivers. These structures have been attributed to valley-side deformation by Saale ice as it penetrated south up the valleys (De Jong 1967).

2. Möns Klint Type (islands and peninsulas) The Danish islands and peninsulas in the Baltic Sea show many magnificent thrust and fold structures developed in chalk and in the overlying Tertiary and glacial sediments.

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Deformation by Weichsel ice during its constricted exit from the Baltic Sea has been postulated (see Hansen 1965).

3. Missourri Coteau Type (scarps) A large, NW-facing scarp in Saskatchewan and Alberta is the site of numerous thrust-out folds overturned to SE and developed in soft Cretaceous sediments. It has been concluded that ice known to have moved from the NW has deformed the scarp (Kupsch 1962).

4. The Elkton Rift Type In Ohio a till-filled rift is developed on an interfluve, parallel to the nearby valley. A raft of Coal Measure rocks has been displaced laterally toward the valley to create the rift. It has been argued that in this case ice moved away from the valley side (Lessig & Rice 1962).

Formation of Glacitectonic Structures

In both the compressional (1-3) and tensional (4) types the following factors in some combination seem to be important in the development of glacitectonic structures:-

(a) a topographic slope (see Charlesworth 1957, Moran,1971),
(b) pore water pressure in sediments,
(c) ice generally at melting point at base (except marginally),
(d) water drainage towards ice-margin from both ice and land,
(e) shallow layer of frozen ground, possibly (Mathews and McKay 1960).

Contorted Drift of Norfolk

Much evidence from mapping, petrological and mineralogical studies now supports the conclusion that the Contorted Drift lithologically consists entirely of the three Cromer Tills, together with the interbedded Intermediate Beds and Mundesley Sands and the overlying Gimingham Sands and Brick Kiln Dale/Briton's Lane Gravels

(Banham 1968). In general, deformation of this sequence increases from SE to NW.

1. Major Folds Around Mundesley, broad open basins and domes affect only the upper part of the sequence - Third Cromer Till and Gimingham Sands. Further north, around Overstrand, these domes and basins involve all beds with the exception of the First Cromer Till and Intermediate Beds in places. The sinking of the large basins has been accommodated by the lateral and upward movement of the underlying beds into the adjacent domes. Symmetrically developed, overturned isoclinal folds reflect this movement and are especially well developed in the Second Cromer Till and Mundesley Sands.

Even further north and west, between Cromer and Weybourne, the entire Cromer Tills, etc. sequence, plus portions of the Cromer Forest Bed Series below, has been deformed during similar, but more intense, folding consequent on outflow of materials from under basins and upflow into domes.

These structures, which have no regional preferred orientation, and which were initiated at the Third Cromer Till/Gimingham Sands (clay/sand) interface are regarded as diapiric.

2. Chalk Rafts These are perhaps the best known feature of the Norfolk coast sections. They are most often viewed between Cromer and Sheringham where their highly variable attitudes (some are even overturned) are due to the dome and basin folds already described. Further SE, where later folding has been less intense (i.e. at Sidestrand and Trimingham) the thrust masses strike generally E-ESE and dip N-NNE. As the lowest, First Cromer Till, on independent evidence, is known to have moved from the NNE it is concluded that the chalk rafts were emplaced during the advance of the First Cromer ice. Moreover, Peake and Hancock (1961) have shown on palaeontological evidence that rafts have moved approximately along the strike of

fossil zones in the underlying solid chalk (i.e. approximately N-S).

Discussion

The chalk rafts and certain associated minor folds appear to have been formed during "classical" glacitectonic deformation. The low-angled slope into the North Sea basin suggests a reduced version of the Missouri Coteau (scarp) type of site.

On the other hand, the later major dome and basin and associated isoclinal (etc.) folds appear to have been formed by diapiric flow of the clay-rich Cromer Tills. The Gimingham Sands and Britons Lane Gravels reach a maximum thickness of 60m. (approximately) around Cromer, and are thought to have provided the load which initiated these diapiric movements. Geotechnical studies by Kazi and Knill (1969) have shown that in comparison with standards at Happisburgh, lithologies in the Contorted Drift near Cromer are doubly overcompressed.

Structures of similar style and/or size are known from the Mississippi Delta ("mudlumps"; Morgan *et al.* 1968) and from a great variety of geological environments (see O'Brien 1968).

Conclusions

Suggested sequence of events in North Norfolk:

1. Advances (3) of Cromer Ice from North Sea basin; emplacement of rafts during the first advance.
2. Deposition of Gimingham Sands and Briton's Lane Gravels (outwash from Lowestoft ice in large part?).
3. Diapiric flow of Cromer Tills, etc. under the weight of overlying sands and gravels to form domes and basins and associated folds.
4. Truncation of these structures by the present topography seems to imply considerable post-Britons Lane Gravels erosional dissection, especially near the coast.

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THE TWO-TILL PROBLEM IN WEST NORFOLK

(a summary of the Presidential Address for 1974, delivered 13 January 1975)

H. EVANS*

Two superposed tills have been exposed at Bawsey, Hillington, North Runcton and in the Nar Valley. The last three sites were only temporarily exposed and the Bawsey site is therefore regarded as the 'type' locality. In each case the junction between the tills is sharp, and no evidence for an erosion surface or palaeosol has been recorded.

The till succession for the area has been outlined in Fig. 1, with each till assigned to a lithologic or colour characteristic. This has been done to avoid a stratigraphical bias that might be implied by familiar stage names.

The Lower Till

This is defined by the interdigitation of Blue Till with a Ferruginous Till and outwash sands and gravels. This type of succession has only been found within the Bawsey area, where it caps the higher ground. Borehole data, supplied by British Industrial Sands, show a blue chalky till capping up to 4.50 metres of mixed ferruginous sands and gravels with discontinuous beds of red-brown clay. The basal contacts are with Sandringham Sands, and only one site has been found where a Blue Till caps Carstone. The outwash phase is mainly found within subglacial channels, where sub-angular boulders of chalk, flint and carstone are contained within a matrix of poorly sorted coarse sands. Laterally the outwash can be well-bedded and sorted. At two sites ferruginous sands with thin silts alternate with poorly sorted chalk pebbles

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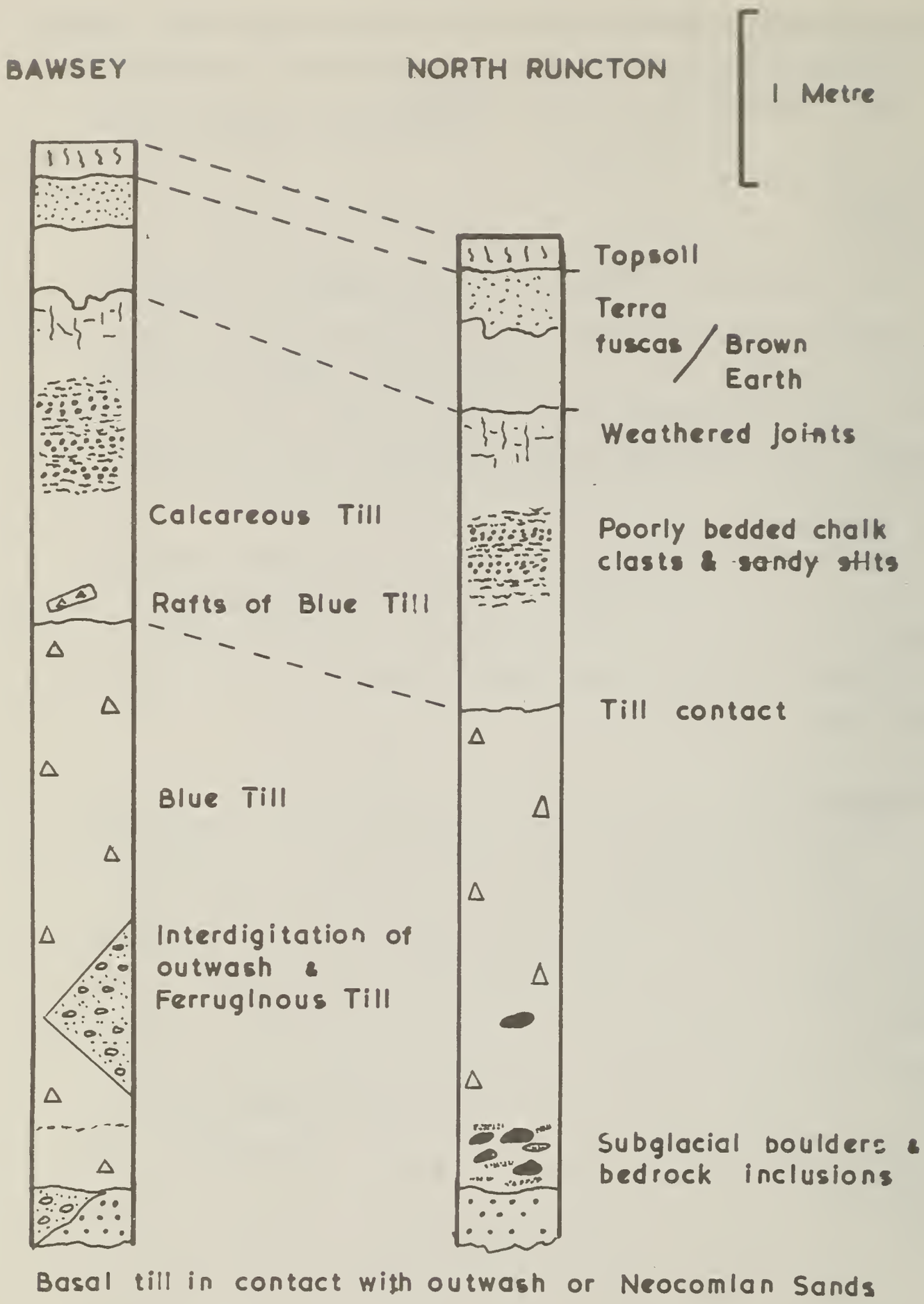

Fig. 1. Sections illustrating the two-till succession within West Norfolk.

and rock flour, the latter unfilling the matrices. The succession passes up to basal lodgement till and in total shows the passage from pro-glacial lake deposition to glacial advance. The pebbly beds in particular show small scale shearing and thrusting with a northerly orientation.

The interdigitation of both tills is particularly well seen where the Blue Till lies in sharp planar contact with outwash sands. The till contains pods and laminae of Sandringham Sands indicative of flow tills (Boulton 1968, Hartshorn 1958) where sub-aerial washing has dissected small channels, which later become infilled. One site shows a ferruginous flow till capping the washed surface of Blue Till. In this case the small channel features have been step-faulted subsequent to melt-out of stagnant ice blocks.

The lithology of the Ferruginous Till shows a dominance of Neocomian erratics of local derivation. The presence of Juassic material is particularly interesting in terms of the interdigitation of tills, and contains a suite of typical fossils and rock-types. the lithology of the Blue Till does not differ significantly from the comprehensive list compiled by Baden-Powell (1948) and contains a high percentage of Jurassic material. The erratics are highly angular within the basal till section. Kimmeridgian shales retain their fissile nature and can form either irregularly displaced slabs, or imbrication with strong up-glacier dip. Chalk clasts are faceted and gouged with percussion marks typical of subglacial transportation. At North Runcton large doggers are often striated and gouged. Examination of material within the -1 Ø to 1 Ø grade showed that up to 50% of total sands consisted of derived Sandringham Sands.

The roundness of chalk clasts increases up the succession from 0.35 basally to 0.48 (Roundness Index, Krumbein 1941) at 2.0 metres. It was found that there was no significant difference in roundness across the boundary of superposed tills.

At both Bawsey and North Runcton basal sections showed evidence for up-shearing of bedrock, and in one instance the bedrock sands had been folded. Reference has already been made to the shearing of outwash material. Similar northerly directional trends were found at North Runcton though it is realised that these will vary considerably with the changes of the subglacial terrian.

The Blue Till lithology indicated a flowpath for glacial advance from between west and north-west across the Wash and North Sea (see Fig. 3a), while the angularity of erratics shows a short distance of transport from the source area. The lowest 1.50 metres of the till are indicative of subglacial lodgement till, particularly where shearing is operative. Above this the lack of textures makes classification difficult.

The Calcareous Till

This till lies in planar and sharp contact with the lower Blue Till over much of the area exposed. The exception to this is at Bawsey where compressive forces have up-sheared segments of the lower till. The colour range of this till is white - creamy white, weathering to a light brown at the surface. At the top of the succession the till shows variable soil horizons from site to site which range from rendzinas to podsols. The till matrix is of a chalky-sandy nature but can consist of nearly pure chalk where boulders have been only partially comminuted during transport.

Compared with the lower till there is a great increase in chalk erratics which comprise up to 75% of all erratics. The general absence of both Jurassic and Carstone derivatives is perhaps significant, and suggests that these outcrops were not exposed following the deposition of the lower till.

Textural changes within the Calcareous Till are not readily discernible, and though some chalky gravel spreads are found they do not provide conclusive evidence for interpreting the depositional environment. Only one site

has been an asset in this respect, and this resulted from the slump of a till face. The fresh surface contrasted remarkably with the creamy colour described above.

The till showed a succession of bedded units with each unit passing up from subrounded chalk pebbles to oxidised angular sands and subordinate silts. The sands contained irregular undulating lenses of Calcareous Till. Each unit varied in thickness from 0.27 to 0.46 metres, and the total thickness was 2.20 metres. The pebble phase showed lateral changes in thickness, while the upper surface was irregular and infilled with the silty sands. The degree of oxidation increased rapidly across the junction. The whole sequence was similar to glacigenic deposits seen in Spitzbergen, where flow tills form an integral part of gravel-till supraglacial deposition. Similar sequences in the New England States have been classified as ablation till (Flint, 1961, Pessl 1968, Drake 1971).

The Contact Zone

The junction of the superposed till has previously been described as sharp and planar, though some Bawsey sections display tectonic features. These are in no way considered as post-depositional slumping which does exist in some sections. The junction is generally of very low relief and shows a slight slope to the WNW.

Along some sections the contact shows the up-shearing of bands of lower till which dip downslope at less than 15 degrees. At such a contact the till underlying the shear bands becomes overconsolidated and there is evidence for crushing within them. In contrast, flames or fingers of lower till overturn in the upslope direction. The latter appear to be consistent with ice advance across a wet till surface.

The most significant structural features are large rafts of lower till which can lie up to 1.50 metres above the junction of the tills. The largest raft was about

3.0 metres in length and 0.80 metres in thickness. The margins of the rafts showed well aligned and reorientated clasts, in contrast to the interior, which was unaffected. The upper surface of one raft showed both shear and drag folds subparallel to the upper raft surface. These rafts had only been subjected to short distance transportation which was evident from irregular trains of Blue Till dipping down towards the junction.

The observations support the theory that the upper till (Calcareous) has advanced across the lower, with rafting occurring in zones of compression within the glacier ice. This may have been due to advance upslope. The directional significance of these structures indicates advance of the till from a direction between NNW to WNW (see Fig. 3b).

Close examination along the junction of the tills and the rafted material gave no indication of a palaeosol or outwash material.

Mechanical Analysis

Samples analysed from the lower till (Blue) for both Bawsey and North Runcton show a mean modal range from 1.6Ø to 2.6Ø(medium to fine sand) and a mean of 2.3Ø(fine sand). The cumulative percentage curves (Fig. 2a) show good grouping and all are strongly fine skewed. This till is characterised by a high sand content relative to fines, with the mean for all samples being 86.8% sand, 7.63% silt and 5.48% clay. Basal tills tend to show a greater percentage increase in the sand grade.

The consistent deficiency within the clay-silt grade suggests that this till may have been well washed of fines, and that its origin is that of a flow-till. Previous authors(Holmes 1941, Gravenor 1952) have shown that glacial advance across shales quickly produces a high clay till.

In contrast, Hoppe (1963) considered clay-poor till as subglacial lodgement on the evidence of immaturity of comminution and angularity of debris. The sand grade of West Norfolk tills show a diminution in shale debris,

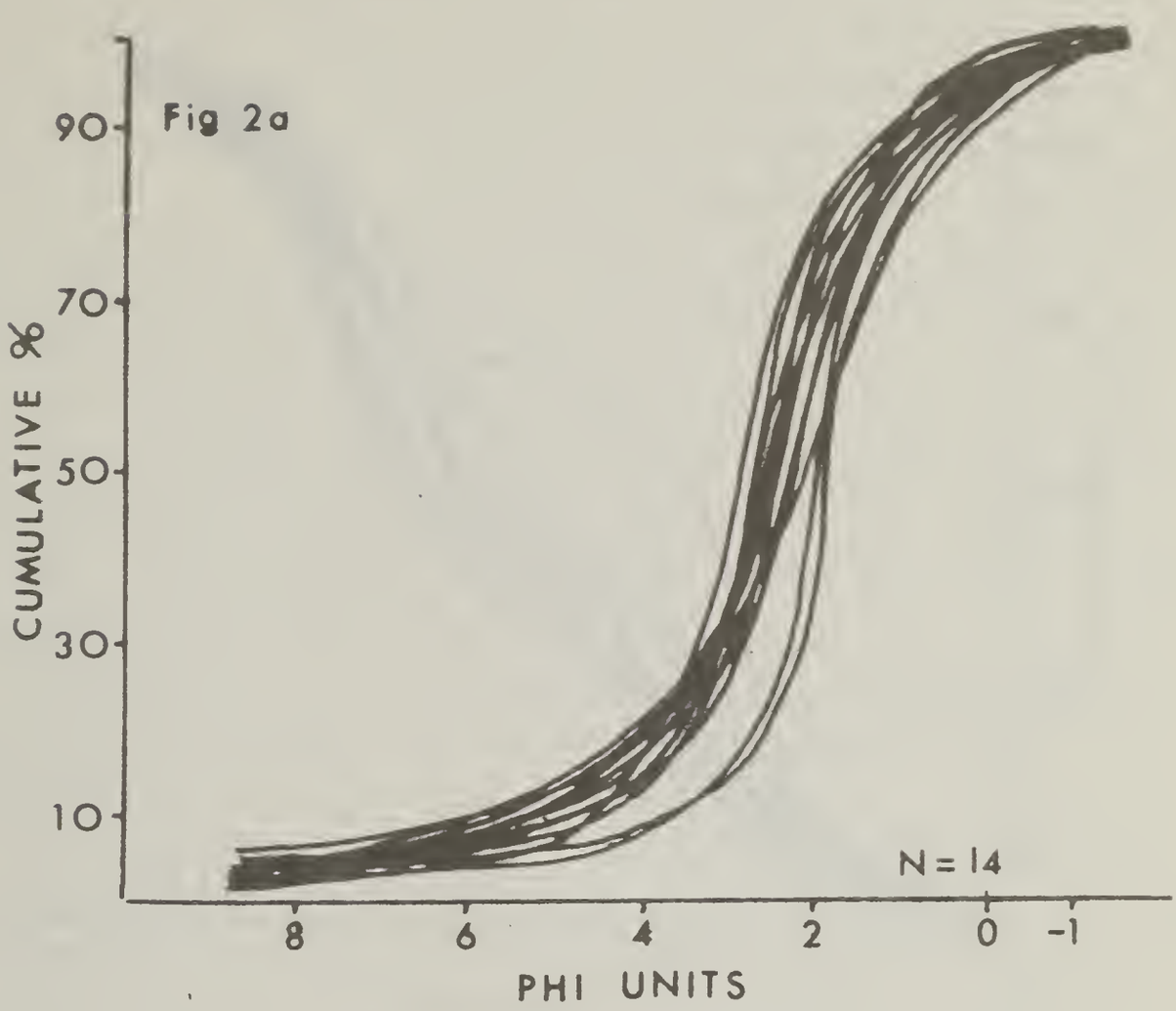

Fig. 2a Cumulative percentage curves for the lower (Blue) till.

within the sand grade, up the succession, so that comminution has not been as effective as one might imagine. Certainly the lower 1.50 metres of the lower till is considered to be subglacial lodgement based on structures and coarseness of debris.

In contrast the Calcareous Till shows an increasing percentage of both silt and clay, while the sand content decreases significantly. The mean modal range for all samples is from 3.6Ø(very fine sand) to 6.0Ø(medium silt) with an overall mean of 4.42Ø(coarse silt). The cumulative percentage curves (Fig. 2b) are mainly bimodal, the exception being three finely skewed samples taken from thrust areas. The mean for all samples is 54.5% sand, 32.9% clay and 12.3% clay.

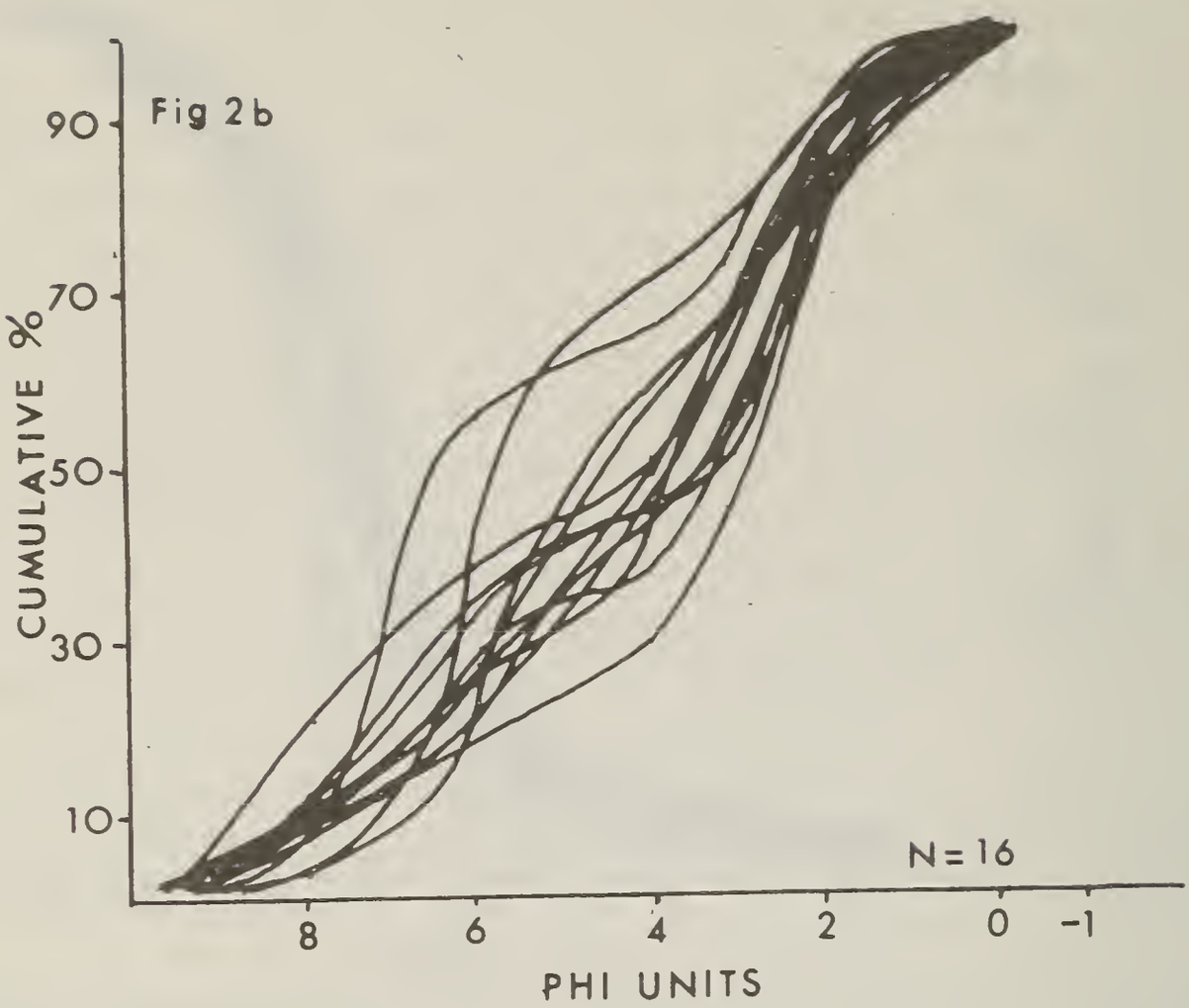

Fig. 2b Cumulative percentage curves for the upper (Calcareous) till.

The textural features of this till are perhaps more helpful in defining the depositional environment than the analyses. Many authors have used a wide range of silt-clay percent to define 'ablation' tills. Dreimanis and Vagners (1970) show that comminuted calcareous rocks are likely to produce a high silt content. My own view is that textural considerations demonstrate that this till is of flow origin in part, that is in those sites lacking compressive textures.

Fabric Studies

Orientation studies were taken at sites where a relatively complete section was exposed. This enabled me to make comparative fabric studies between both tills

in terms of vertical and lateral variation. Significant maxima for each sample have been analysed individually using Fisher's (1953) function for probability density on a sphere(Steinmetz 1962), which gives orientation of a resultant vector $\bar{A}$, its magnitude, a radius circle of confidence (θ), and a precision parameter (K). The results show that (K) values are less than 3.0 while (θ) values show a wide dispersion about the vector. Samples do not show spherical normal distributions.

When plotted on a Schmitt equal-area projection of the lower hemisphere all samples are distributed close to the primitive. Mean dips for samples are less than 15 degrees. The strength of secondary maxima increases up the succession for both tills.

A summary of results follows in which comparison is made with structural data from the tills; Fig. 3a/b illustrates the results of analyses.

a. Five samples taken from subglacial sections of the lower till. Two samples from North Runcton, and one from Bawsey, showed orientations between west and north-west, the others were transverse to this direction. Structures at both localities showed orientation between north and north-west.

b. Samples taken at depths between 0.30 to 1.00 metres below the junction showed that only two, for North Runcton, had a north-west orientation. All other samples were transverse to this direction.

c. Above the junction six samples taken within the <u>Calcareous Till</u>, showed a consistent north-east to south-west trend, and only one sample at Bawsey had a north-south orientation. The preferred orientation of rafted material within this till was found to be west-north-west to north-north-west which is regarded as the significant orientation for ice advance. This trend appears to be fairly consistent with measurements for Gipping Till made by West and Donner (1956) for sites 1, 9 and 10.

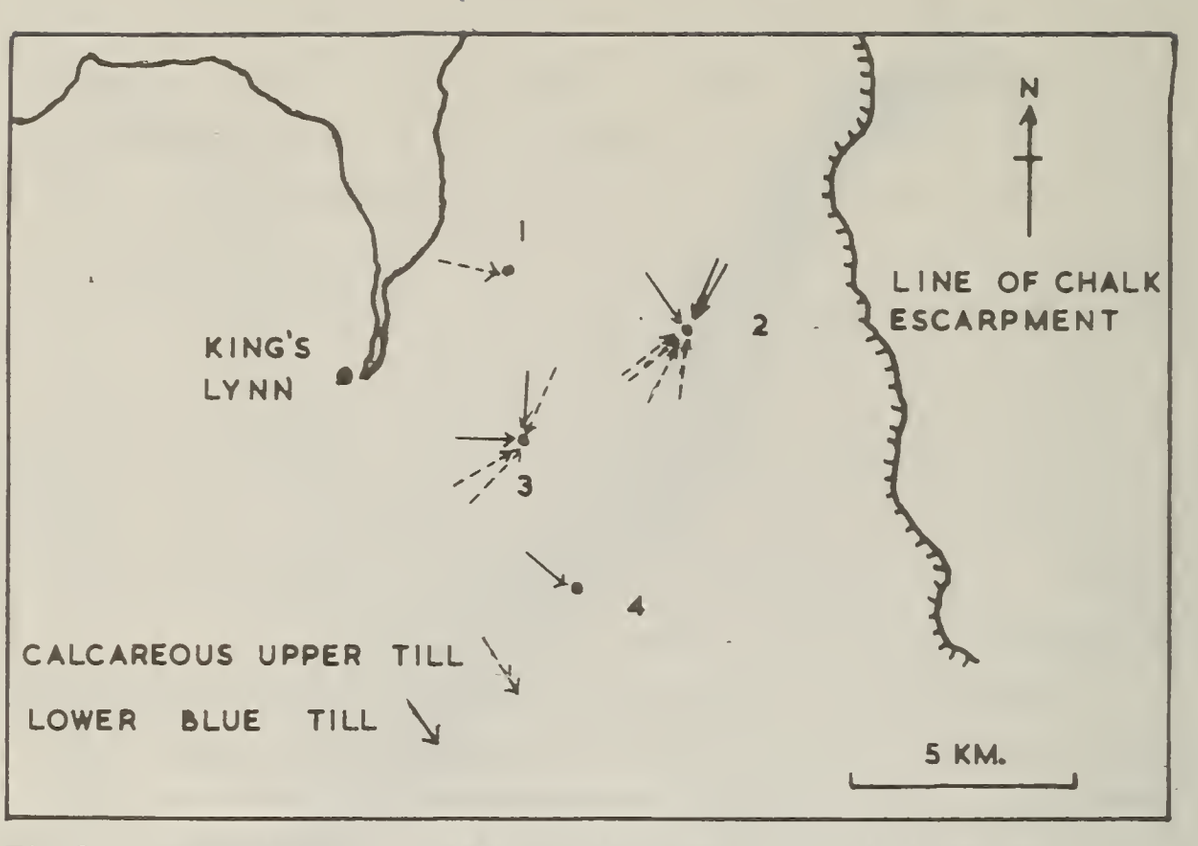

Fig. 3a MAP SHOWING THE DIRECTION OF PREFERRED ORIENTATION FOR BOTH TILLS. SITE LOCALITIES ARE 1. RISING LODGE, 2. BAWSEY, 3. NORTH RUNCTON, 4. NAR VALLEY.

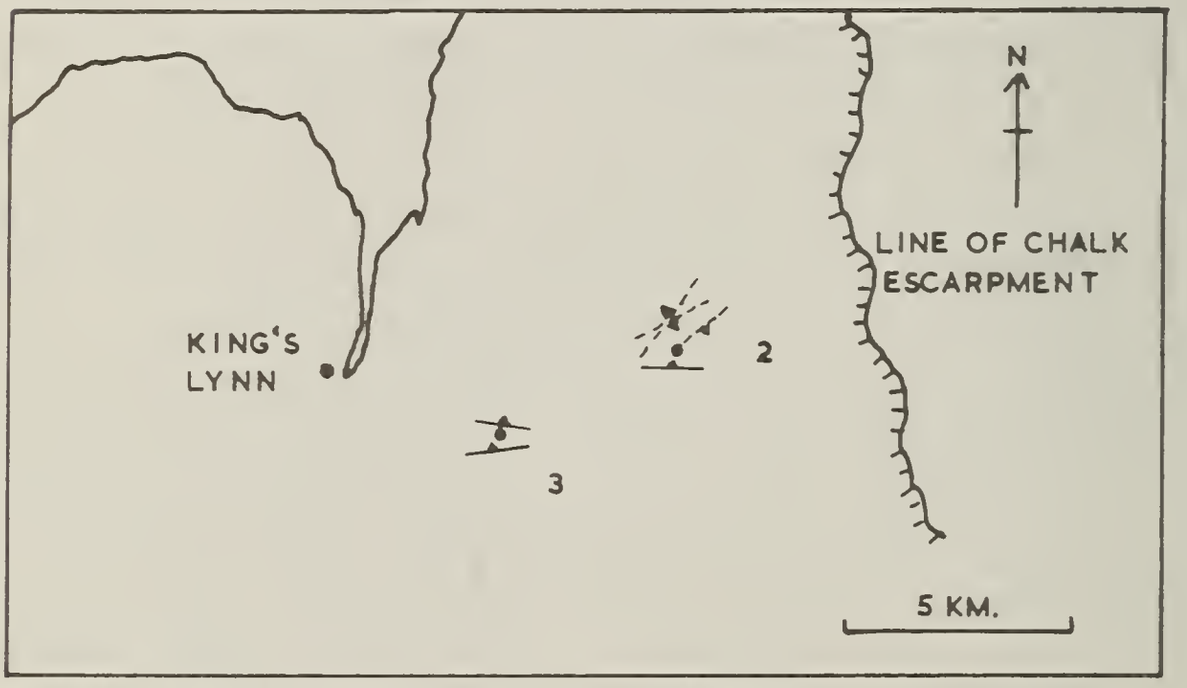

Fig. 3b MAP SHOWING THE STRIKE OF MAJOR STRUCTURES WITHIN THE SUBGLACIAL BLUE TILL (—▲—), AND CALCAREOUS TILL (-▲-) WITH RAFTED INCLUSIONS.

Vertical sections taken across the junction show that the north-east to south west orientation is common to both tills, and may suggest reorientation of the lower till (MacClintock and Dreimanis 1964, Penny and Catt 1967).

Conclusions

1. That the lower till (Blue) advanced from a north-westerly direction - based on structural elements, fabric studies and lithology. This stage of ice advance shows interdigitation with a ferruginous till and outwash which is only evident within the Bawsey area. Both tills contain a high percentage of angular erratics and these are mainly of local derivation with a short distance of transport from their source areas. Bawsey is only some 6 kilometres from the Jurassic outcrops. The lower part of the Blue Till is definitely subglacial lodgement though the lack of change in comminution up the succession suggests that it could be lodgement throughout.
2. The upper till (Calcareous) shows lateral variation of textures between contrasting zones of compression with those of extensive flow. The former is exemplified by shearing and rafting across an otherwise sharp planar contact, while the latter consists of flow till in part. The compression may well have been due to advance uphill from the Wash. The presence of rafts shows that this till advanced across the lower till from a direction close to that observed for the lower till.
3. The lack of palaeosol or outwash at the junction suggests that insufficient time elapsed for either an interstadial or interglacial period.

The most likely explanation of the two-till problem is that the upper till is a readvance phase across a stagnating lower till, and that both tills are of the same glacial stage. Brickearths with scattered Cardium, Ostrea and Buccinum are found to overlap a till succession 500 metres to the north of the Bawsey Site. Rose mapped these

Fig. 4 Section showing the planar contact between the Blue and Calcareous Tills.

Fig. 5. Large raft of Blue Till within the Calcareous Till; the upper surface of the raft has been sheared with a prominent nose to the right.

deposits as Nar Clay in 1865. Confirmation for the age of these beds has not been fully established, but I tentatively suggest that the tills may well be Anglian in age.

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Received March 1975.

SECRETARY'S REPORT FOR 1974

The normal venue for meetings at the University of East Anglia seems to have established itself fairly well, thr ugh there is sometimes some difficulty experienced by newcomers in finding the relevant lecture room. Throughout 1974 we were obliged to use no less than four different rooms in the University. With the opening of the Library extension it is hoped that the use of the Library Conference room will become the room.

During the year the following lectures took place: January: Dr. P.N. Chroston on "Geophysical Investigations of the Palaeozoic Floor of Norfolk", followed by a demonstration of geophysical equipment. February: Professor J.C. Cummings on "The San Andreas fault and Californian Geology". March: Dr. G.S. Boulton, at a few hours notice, gave a talk on "Aspects of glacial deposits, Recent and Quaternary", for which we are all very grateful as Dr. Banham, who was scheduled to lecture, was unfortuaately prevented from doing so by an attack of 'flu. November: Dr. P. Banham on "Aspects of contorted drift". December: The A.G.M. was followed by showing of members' slides and demonstration of speciments.

The standard of lectures throughout the year has been consistently high and on behalf of the Society I would like to thank the lecturers who have provided a stimulating programme.

February 1975. Christopher J. Aslin.

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The Geological Society of Norfolk exists to promote the study and knowledge of geology, particularly in East Anglia, and holds monthly meetings throughout the year.

Visitors are welcome to attend the meetings and may apply for membership of the Society. For further details write to the Secretary: Dr. C.J. Aslin, The University Library, University of East Anglia, Norwich NR4 7TJ.

Copies of this Bulletin may be obtained, £1 (plus 20p postage), from the Secretary at the address given above; it is issued free to members.

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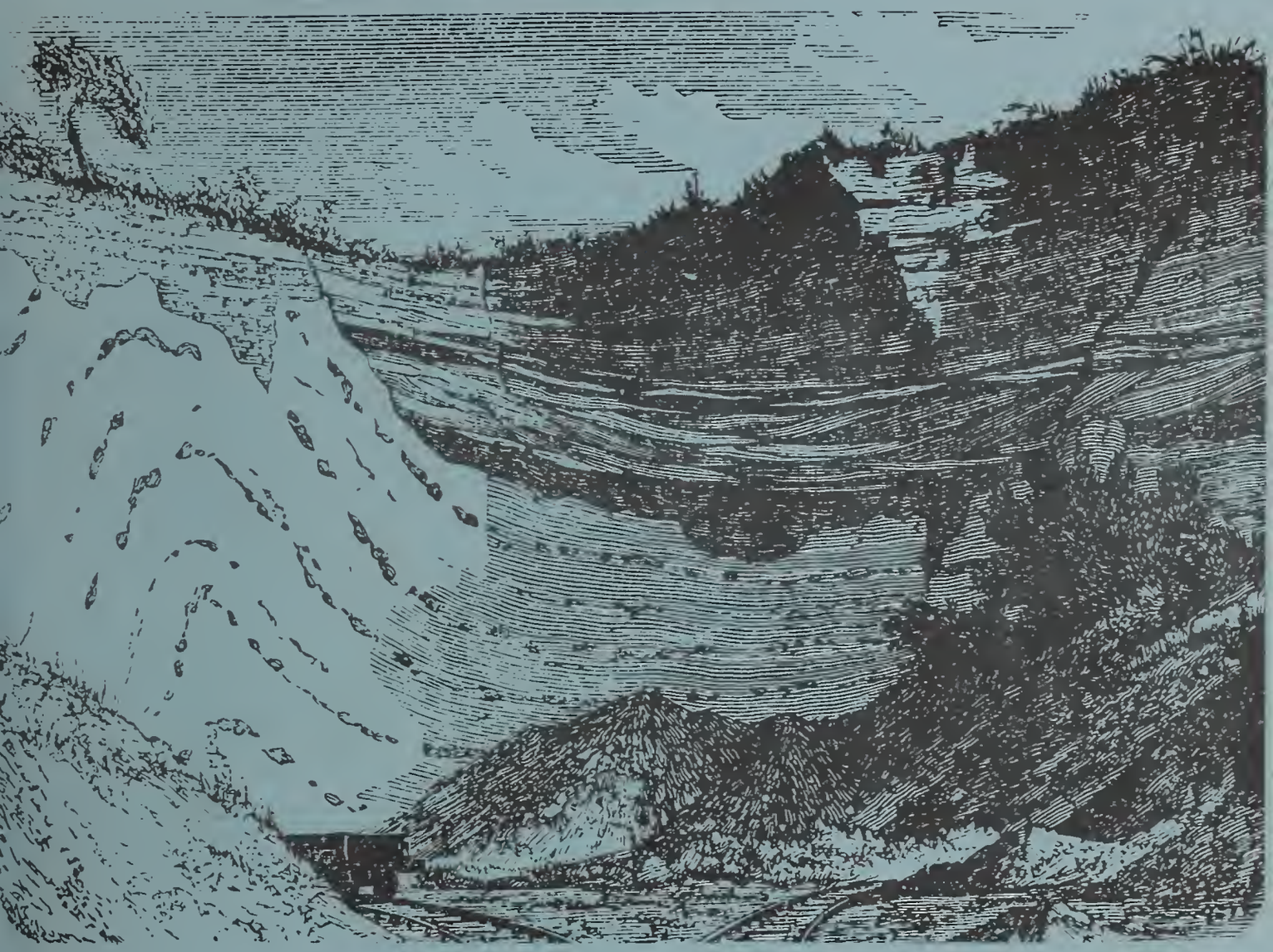

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No. 28 April 1976

Editor: R.S. Joby

116 Gowing Road, Norwich NR6 6UQ

EDITORIAL

Our policy of having a double or annual edition of the Bulletin is continuing this year as part of our policy to keep prices low. We must be the society with the lowest subscription charge in Norwich by now, which has both publications and meetings included in that very low annual charge. Not a little of this is due to facilities provided by the University of East Anglia, and the careful housekeeping of our Treasurer. Our thanks are also due to Norman Peake, who has organised many field trips over the last few years, but is now stepping down. His deep knowledge of the Chalk has been at our service unstintingly and we have learned much from him.

The Presidential Address this year was stimulatingly, not to say provocatively, delivered by Professor Keith Clayton, who is already well-known to us all. His theme of coastal erosion drew engineers into the discussion which followed, providing us with other views on a subject of continuing interest for all, and continuing worry for some. Our other contributions this time include a paper from W.M. Corbett and C.A.H. Hodge of the Soil Survey on the Drift deposits behind Sheringham, and a further contribution of interest to engineers from P.F. Wilkes, of the County Highways Department, on highway engineering.

Bulletin 29 will be issued in April 1977. Contributions should be sent to me as soon as possible, and certainly <u>no later than 31 October 1976</u>.

Will contributors please note that manuscripts are acceptable in legible handwriting, although typewritten copy is preferred. In either case it would be a great help if details of capitalisation, underlining, punctuation, etc., in the headings and references (particularly) could conform strictly to those used in the Bulletin.

Illustrations intended for reproduction without redrawing should be executed in thin, black ink line. Thick lines, close stipple, or patches of black are not acceptable, as these tend to spread in the printing process employed. Original illustrations should, before reproduction, fit into an area of 225 mm by 175 mm; full use should be made of the second (horizontal) dimension,which corresponds to the width of print on the page, but the first (vertical) dimension is an upper limit only. All measurements in metric units, please

R.S.J.

Bull. geol. Soc. Norfolk, 28, 3-27 (April 1976)

DISTRIBUTION AND LITHOLOGY OF DRIFT BEHIND SHERINGHAM, NORFOLK

W.M. CORBETT and C.A.H. HODGE*

Introduction

"After spending about a year in Norfolk I began to believe I knew all about the Drift, but during the following seven years of my sojourn in that county, as I moved from place to place, I somehow seemed to know less and less; and I cannot say what would have been the result, but fortunately the Geological Survey of the county came to an end." (Woodward 1885)

The soils of Ordnance Survey sheets TG 13 (Barningham) and TG 14 (Sheringham), covering much of the Cromer ridge, were mapped by the Soil Survey of England and Wales during 1968-69.

Geological sources for the western half of the Barningham/Sheringham sheet are the Geological Survey Old Series Sheets 68 N.W. and 68 S.W. and the accompanying memoir (Woodward 1884) and for the eastern half Old Series Sheet 68 E. and its memoir (Reid 1882). The mapping of the area now covered by Ordnance Survey Sheets TG 13/14 was split between these two officers, Reid covering the northern two-thirds between 1876-80, and Woodward the southern one-third during 1876-83. The complexity of the district forced them to compile essentially lithological maps (Table 1). The mapping was shared but there is divergence in the lithological keys, blue being used for Calcareous masses or Marl on Sheet 68 E, for Marly Clay and Loam (Contorted Drift etc) on 68 N.W., and for Boulder Clay (i.e. Chalky Boulder Clay) and Marl on 68 S.W. Other workers who have written about land within TG 13/14, mostly with reference to the

* Soil Survey of England and Wales, Government Buildings, Block B, Brooklands Avenue, CAMBRIDGE CB2 2DR

coastal cliff sections, are Boswell (1916), Solomon (1932), Banham (1965, 1968), Banham and Ranson (1965) and Ranson (1968). West (1957), Sparks and West (1964) and Straw (1965) have considered the geology in relation to landforms mainly for the district around Holt immediately west of TG 13/14.

Data on soils within TG 13/14 were obtained by augering with an inch diameter 3 ft. (1 metre) screw auger at an intensity of 30-55 bores per square kilometre. Analyses, including calcium carbonate content and particle size distribution were made by the Soil Survey's analytical section, using samples from specially dug soil profile pits. Some samples were also taken from deeper cores and from exposures in disused pits, for analysis of calcium carbonate content and particle size distribution by Dr. R.M.S. Perrin and his staff at the School of Applied Biology, University of Cambridge. Particle size analyses by the Soil Survey are plotted on triangular co-ordinate diagrams and those by Dr. Perrin, with smaller grade intervals, as cumulative curves.

Three soil parent materials have been identified; a brown drift, a marly drift, and a cover loam, and their distribution is shown in Figs. 1, 2, 3 and 4. Their distribution and lithology as established by soil survey is of interest especially as the area is important in the East Anglian Pleistocene stratigraphic succession (Bristow and Cox 1973).

The Brown Drift

This is within auger depth over much of the south-east quadrant of TG 13/14 at heights between 75 ft (23 m) and 175 ft (53 m) O.D. and on higher ground between 200 ft (61 m) and 250 ft (76 m) O.D.

TABLE 1 INDEXES (LEGENDS) OF OLD SERIES GEOLOGICAL MAPS 68 N.W., S.W.AND E.

System	Map Colour	Map description			
		68 N.W.	68 S.W.	68 E.	
Post Glacial	pale brown	alluvium	alluvium	alluvium	
	brown	-	-	River Gravel	
Glacial	red	Gravel and Sand	Gravel and Sand	Sand and Gravel	
	yellow	-	-	Loam and clay with nests of sand,etc.	Contorted Drift.
	blue	Marly Clay and Loam (Contorted Drift,etc.)	Boulder Clay and Marl	Calcareous masses or Marl	
	yellow	-	Loam	Loam and Clay with nests of sand, etc.	
	red	-	Sand and Gravel	-	

between Hempstead and West Beckham; the Glaven catchment on the Cromer Ridge (Figure 1). On the coastal plain it is on either side of Sheringham between the sea-cliffs and the 175 ft (53 m) contour marking the north face of the Cromer Ridge on the adjacent Kelling Heath (Holt) outwash plain to the west. This area has Brown Drift within auger depth or, on the evidence of gley morphology of the superficial sand, near the surface.

The material is a brown* unsorted slightly mottled firm sandy loam or sandy clay loam (Table 2, Fig. 5a). It can be seen in a road cutting near Calthorpe (TG 181311). Cox and Nickless (1972) describe Norwich Brickearth near Norwich as structureless till of brown sandy clay, and Boswell (1914, 1916) gives a very similar description, noting that it has field characteristics quite distinct from other deposits and a constant particle-size distribution over an area of 350 sq. miles north and east of Norwich. These descriptions match those of the Soil Survey and, allowing for differences in technique, Boswell's particle-size distribution, for samples from one site at Cawston about 3 miles to the south of TG 13/14, are also similar. The Brown Drift found in the south-east quadrant of the map is thus regarded as a north western part of the Norwich Brickearth outcrop. The area of Brown Drift in the south-east of TG 13/14 is broken up in Fig. 1 because of numerous valley floors with superficial deposits which separate the outcrops of the drift.

---

* Colour names and notations are those of the Munsell Soil Colour Charts.

Figure 1. Brown Drift (Norwich Brickearth, Contorted Drift) behind Sheringham.

Brown drift on the Cromer Ridge on the south side of the Glaven valley between Hempstead and West Beckham and on the Coastal Plain is lithologically similar to the material in the south-east quadrant of TG 13/14 (Table 2). On the coastal plain it was identified in auger borings as far west as Weybourne.

The distribution of the "Loam and Clay with nests of sand,etc." of the Contorted Drift in the Old Series geological map 68 E. is broadly similar to that of the Brown Drift in Fig. 1, but on 68 N.W. no distinction was apparently made between Loam and Marl which are grouped,and no separate outcrops are shown between Sheringham and Weybourne. On map 68 S.W.,where Loam was distinguished,the outcrop in the Glaven valley is displaced to the south east in relation to the Brown Drift shown in Fig. 1.

Well records held by the Institute of Geological Sciences show the core of the Ridge in the western and central part of TG 13/14 is clay, thinner sand and gravel separating this from a level chalk surface beneath. This suggests the Brown Drift extends laterally along the Ridge to the Contorted Drift in the coastal cliff, outcropping within the ridge in the Glaven valley. There are, however, no well records east of Sheringham to confirm this. South of the ridge in the south-west of TG 13 the records show thinner clay under sand and gravel.

The Marly Drift

This is the Marly Drift of Woodward (1884) and Straw (1965), a very pale brown to white, very calcareous firm drift,fairly free of non-chalk stones (Table 2). Calcium carbonate is often 70 and

TABLE 2		BROWN DRIFT (NORWICH BRICKEARTH)		
Map Reference	Depth (cm)	Description	$CaCO_3$	Texture
Coastal Plain TG 132432	98-120	strong brown 7.5YR 5/6 faintly mottled, reddish-yellow 7.5YR 6/8, firm	Nil	sandy clay loam
TG168428	68- 91	brown 7.5YR 5/4, very firm	Trace	loam
Cromer Ridge TG 138389	100-150	brown 7YR 4/4 mottled strong brown 7.5YR 5/8 and yellowish-brown 10 5/8, very firm	Nil	sandy loam
Southern Lowlands TG 160321	61 - 91	brown 7.5YR 5/4 mottled yellowish-red 5YR 4/8 and greyish-brown 10YR 5/2, very firm	Nil	sandy clay loam
TG 161341	6- 90	yellow brown 10YR 5/6 mottled brown 7.5YR 4/2 and strong brown 7.5YR 5/6, friable	Nil	sandy loam
TG 162321	71-102	brown 7.5YR 4/4 mottled strong brown 7.5YR 5/6 and brown 7.5YR 5/3, firm	Nil	sandy clay loam
TG 166378	94-107	light yellowish-brown 10YR 6/4 mottled strong brown 7.5YR 5/8, yellowish-brown 2.5YR 6/2 and reddish-brown 5YR 3/4	Nil	sandy clay loam
TG 193367	70- 91	yellowish-brown 10YR 5/4 mottled yellowish-red 5YR 5/8 and pale brown 10YR 6/3, very firm	Nil	sandy clay loam
TG 198337	48-100	brown 7.5YR 5/4 mottled light olive grey 5YR 6/2 and strong brown 7.5YR 5/6, very firm	Nil	clay

80 per cent but values over 90 per cent have been recorded (TG 161399 East Beckham, 95.6 per cent $CaCO_3$). The field appearance is quite distinct from Brown Drift but the particle-size distribution of carbonate free material (Table 3, Fig. 5a, 6) is variable; some samples are similar to the Brown Drift, others have more clay and silt. Mottling as an indication of impeded drainage seems associated with more clay in the non-carbonate fraction.

In the mapped area there is no spatial pattern in calcium carbonate content but samples at Sustead (TG 186377) and West Beckham on the Cromer Ridge (TG 113339) show decreasing carbonate and increasing non-carbonate sand with depth (Fig. 6). The lowest samples from both places have a particle-size distribution similar to the Brown Drift and carbonate values between Brown Drift and Marly Drift. Similar material was found in the south-east in Wolterton Park to the south of other Marly Drift outcrops, well within the Brown Drift area.

The largest outcrop is on the coastal plain around Weybourne below the 175 ft (53m) contour which marks the north edge of the Cromer Ridge (Fig. 2). Elsewhere it is in small isolated outcrops, on the coastal plain between Weybourne and Sheringham, on the ridge south of Sheringham and between Hempstead and West Beckham, and to the south again at about 175 ft (53 m) along the southern margin of the ridge. There are a few still further south in the area of Brown Drift.

Most occurrences on the ridge are to the north and south and are closely associated with Brown Drift. This is true of the

Figure 2. Marly Drift near Sheringham

outcrops on the Ridge and on the coastal plain where brown drift adjoins the main mass of the Marly Drift at Weybourne. The West Beckham (TG 138389) bore passed through Brown Drift into Marly Drift (Table 3). The exceptions to this pattern are occurrences south of Sheringham and in the south-west near Saxthorpe in areas of sand and gravel.

Comparison of the Old Series Geological and Soil Survey maps shows a fairly good agreement on occurrence but very big differences in the extent of the Marly Drift. Geological map 68 E. shows "Calcareous masses or Marl", a subdivision of the Contorted Drift, behind Sheringham around East Beckham and near Felbrigg, the outcrops in each locality covering a considerable area. In the big area of Contorted Drift to the south of the ridge small patches are shown fairly frequently, particularly near the ridge gravels. These are all more extensive than found in soil survey. On 68 N.W. no distinction was made between Marl clay and loam, and no comparison can be made. However on 68 S.W., which covers the greater part of the west side of TG 13/14, Boulder Clay and Marl are mapped together and are shown as widespread in valleys between Saxthorpe and Holt where soil survey showed the Marly Drift to be rare and Chalky Boulder Clay absent.

Reid (1882), noting many marl pits between upper Sheringham and Beckham, commented that the Contorted Drift was more marly to the west. It seems probable that estimation of the extent of Marly Drift from the examination of marl pits alone, might give an exaggerated impression of its extent. In an area of acid sandy soils marl pits would be of great importance and every outcrop exploited,

TABLE 3 MARLY DRIFT IN SOIL PITS

Map Reference	Depth (cm)	Description	$CaCO_3$%	Texture*
Coastal Plain				
TG 114428	55-100	very pale brown 10YR 7/4 stoneless, firm	74.9	silty clay loam
TG 115423	68- 90	very pale brown 10YR 8/4 with yellow 7.5YR 5/4 crack faces, chalk stones, friable	51.0	-
TG 117420	29-100	very pale brown 10YR 8/4, occasional flints, very firm	74.4	sandy clay loam
Cromer Ridge				
TG 138389	150-180	very pale brown 10YR 7/4 with brownish-yellow 10YR 6/8 and light grey 10YR 7/1 mottled, stoneless, very firm	71.3	clay
TG 158359	61-100	white 10YR 8/1 and very pale brown 10YR 8/4 mottled yellow 10YR 7/8 firm	70.0	clay loam

*Texture classes are of carbonate free material

whilst the presence of Cover Loam as a thin superficial deposit in the valleys would tend to obscure the true extent.

Sands and gravels cover most of the rest of the map. On the North side of the Cromer Ridge these are stony and do not contain Marly Drift. South of the watershed between the Bure and the coastal streams, they are stratified sands, with some Marly Drift inclusions. The I.G.S. well records show Marly Drift within the ridge only in the sands and gravels immediately above the clayey core. The close association of Marly Drift and gravel was noted in the district west of TG 13/14 by Straw (1965).

The Cover Loam

The Brown Drift in the lowlands in the south-east and the sands and gravels of the ridge are covered by a thin superficial deposit (Fig. 3). This is a non-calcareous brown loam, and it is the most widespread soil parent material in the district. It is absent from most of the coastal plain.

In profile there is a sharp boundary between it and the underlying drift, a sharp textural change at depths between 40 and 200 cms. A typical section at Hole Farm, Hempstead (TG 115353)shows:-

0- 35 cm, dark yellowish-brown 10YR 4/4 non-calcareous loam, slightly stony.

35- 80 cm, strong brown to brown 7.5YR 5/6-4/4 non-calcareous loam, slightly stony.

80-100+cm, yellowish-brown 10YR 5/8 and yellowish-red 5YR 5/6 non-calcareous very stony sand.

Locally this material is thicker on the gentle north and east facing

Figure 3. Cover Loam

slopes and thin or absent on the steep slopes facing south and west. It is thickest in valleys, dells in valley sides and in other slight depressions in the landscape. The maximum thickness is about 200 cm. It tends to be absent from small crests and narrow ridges.

The nature of the textural change is shown in Fig. 5b. Cover Loam samples with 20 to 50 per cent silt and 5 to 20 per cent clay are a distinct group from sand and gravel with low silt and clay and Brown Drift (Norwich Brickearth) with more clay. It seems unlikely that post-glacial weathering produced such material from dissimilar substrates. Catt et al. (1971), from particle-size and mineralogy, conclude it to be loess with material from below mixed in, and in this area Cover Loam over the Brown Drift tends to have more clay for a given silt content than over sand. Ranson (1968) had previously noted a possible loess deposit on the Cromer Ridge east of sheet TG 13/14. More recently Perrin, Davies and Fysh (1974) have defined the distribution of late Pleistocene aeolian deposits in eastern England and TG 13/14 falls into lithological province IV in which topsoils are enriched in wind-transported silt and sand. Over both sands and Brown Drift the thickness of the Cover Loam increases as the silt content rises and the sand and stones decrease. The exception is the surface plough layer which is almost always slightly sandier than the immediate subsoil. These trends are consistent with Cover Loam being formed by the mixing of loess with the substrata. Periglacial disturbance brought up and mixed tongues of underlying material (Hodgson 1967), and the wind throw of trees and animal burrowings might contribute to this. Particle-

size analysis of loess (Catt et al. 1971), at two places within TG 13/14, give a single distribution curve when the sample has much silt, suggesting sorting from a single source, and a characteristic double curve when there is more sand, indicating a composite material (Fig. 6):

Analyses for Cover Loam occurring on contrasting substrata are available from 29 sites; 20 on sands and 9 on the Brown Drift (Norwich Brickearth). Regressions were fitted to sites and soil properties for these profiles using the Rothamsted MLP programme written for the ICL 4-70 computer. Although the sites were selected to represent soil profile classes separated partly on depth of Cover Loam there was a low correlation of thickness with map position and the sites may thus be regarded as a random selection in space. As expected from field observations silt content was correlated with thickness on the 15 sites where the depth of Cover Loam over sand was measured. The equation z (per cent silt) = -3.97 + 0.62d (depth cms) accounted for 51 per cent of the variance, the regression coefficient being significant at the one per cent level. Correlation of silt content with thickness on the Norwich Brickearth sites was less good so that over all 29 sites only 20 per cent of the variance in silt content could be accounted for in terms of depth.

Of the variates fitted, the best correlation was obtained between silt content, thickness of Cover Loam, and the three figure Eastings co-ordinate of the Grid Reference of the sites. Using the data for the 29 sites, 57 per cent of the variance of the silt can be accounted for by z (silt content) = -13.29 + 0.21e (Eastings)

+ 0.3d (depth cms) the regression coefficients being significant at the 0.1% level. For the 15 sites with a measured depth to sand, 79% of the variance could be accounted for by z = -27.42 + 0.19e + 0.15d, again significant at the 0.1% level. The increase in silt with direction supports the hypothesis that the Cover Loam contains windblown loess. Assuming silt content of loess increases with distance from the source, this lies to the west, or more probably to the north-west as inclusion of the Northing grid co-ordinate as a variate gives a non-significant negative regression coefficient.

Cover Loam is absent from the highest, most exposed parts of the Cromer Ridge above the 300 ft (92 m) contour and from the crest of the steep north face above 200 ft. (Fig. 4). On these surfaces there is more silt in the plough layer than in the subsoil. On the steep north face of the Cromer Ridge the absence of silt could be due to erosion. On high, relatively flat exposed positions it may never have been deposited. It is present on gently sloping land nearby, more liable to erosion. Thick deposits on valley floors often show a more sandy upper part, the product of local movement, and a lower more silty part representing original deposition.

Windborne deposits, either cover sand or loess, are common in Europe. Intermediate sand-loess occurs in Belgium and similar mixed deposits have been described from the Veluwe near Arnhem by Vink (1949). Valley loess there is partly mixed with sand by solifluction. The landscape is similar to Norfolk and the distribution pattern likewise lobate with loess extending upslope in re-entrants and across cols. In both cases the pattern can be correlated

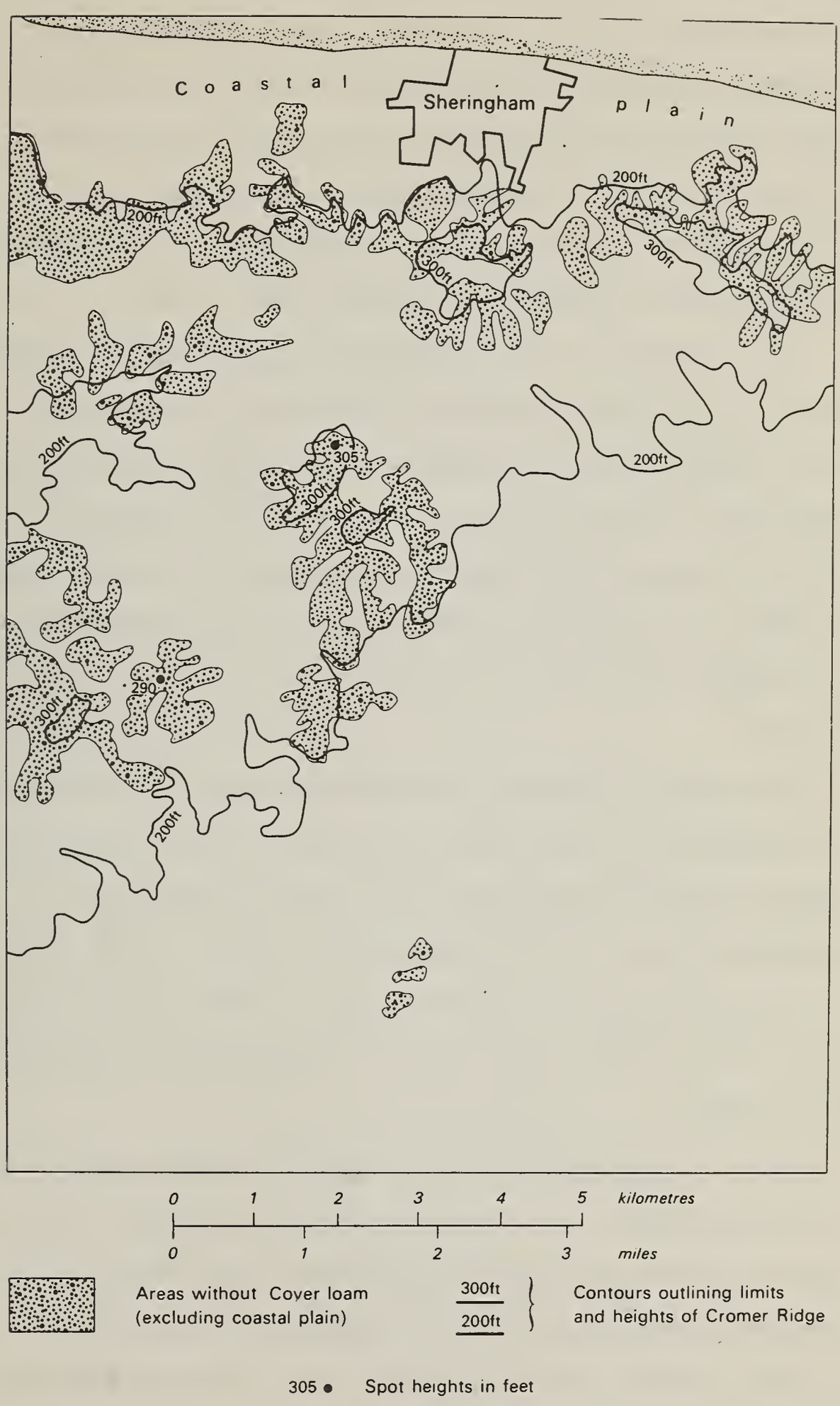

Figure 4. Area without Cover Loam.

imperfectly with relief. Undisturbed loess in Holland has more silt than the Norfolk Cover Loam but loess mixed with sand has a similar particle size distribution. On triangular co-ordinates (Fig. 5b) the particle size distribution of Cover Loam occupies similar space to samples of cover sand and loess taken throughout the Netherlands (de Bakker and Schelling 1966, p. 55).

This thin deposit is not recognised in the Old Series geological maps but on 68 SW the area between Corpusty and Holt mapped as Boulder Clay and Marl has a somewhat lobate pattern, tends to delineate low lying ground and in several places is annotated loamy. It seems probable that the boundaries here are those between the Sand and Gravel and the Cover Loam which was regarded as soil covering Marl.

Discussion

The Ridge is conveniently defined on the north and south by the 175 ft. contour. To the north on the coastal plain around Weybourne is Marly Drift and to the east of this areas of Brown Drift (Contorted Drift, North Sea Drift, Norwich Brickearth). On the south side, the lowlands to east and south east of Matlask are cut in Brown Drift and to the south and west towards Corpusty this is covered by thin sands.

Above this height are sands and gravels, to the south of the Bure watershed laminated sands with few stones and to the north stony sands. The Glaven cuts down in the centre of the ridge to expose Brown Drift above the 175 ft. level marking the Ridge boundary in the north and south. This indicates a Brown Drift core capped by

sand and gravel as postulated from cliff sections at Overstrand.

Marly Drift occurs away from Weybourne only as small isolated outcrops in the Brown Drift near the Ridge boundary,or in the Ridge sands near their boundary with the Brown Drift.

These drifts forming the soil parent materials are distinct and easily recognisable in the field. They form the overall simple pattern summarized above,although the detailed distribution is complicated. A soil parent material map thus parallels the simple arrangement of geological deposits shown at a smaller scale on the Old Series geological maps of the last century. However, the stratigraphy is complex,as is well known from the cliff sections between Weybourne and Happisburgh,and this is obviously also true of the association of Marly Drift, Brown Drift, and Sands observed in mapping sheets TG 13 and TG 14.

Thus no stratigraphic correlation is attempted between the Brown Drift and the 1st, 2nd and 3rd tills (Banham 1968, Ranson 1968) of the Contorted Drift on the coast,or between these and the Marly Drift,or the latter with the Lowestoft till (chalky boulder clay),as this needs more specialised work than can be attempted as an adjunct to a soil survey.

In a wider context Bristow and Cox (1973) have suggested that all these deposits are"penecontemporaneous" and are part of a single glaciation. Before this can be established it is likely that detailed mapping may be needed,especially along the line Fakenham, Foulsham, Reepham which Woodward (1884) indicated as the lithological junction zone between the Chalky Boulder Clay and the Marly Drift.

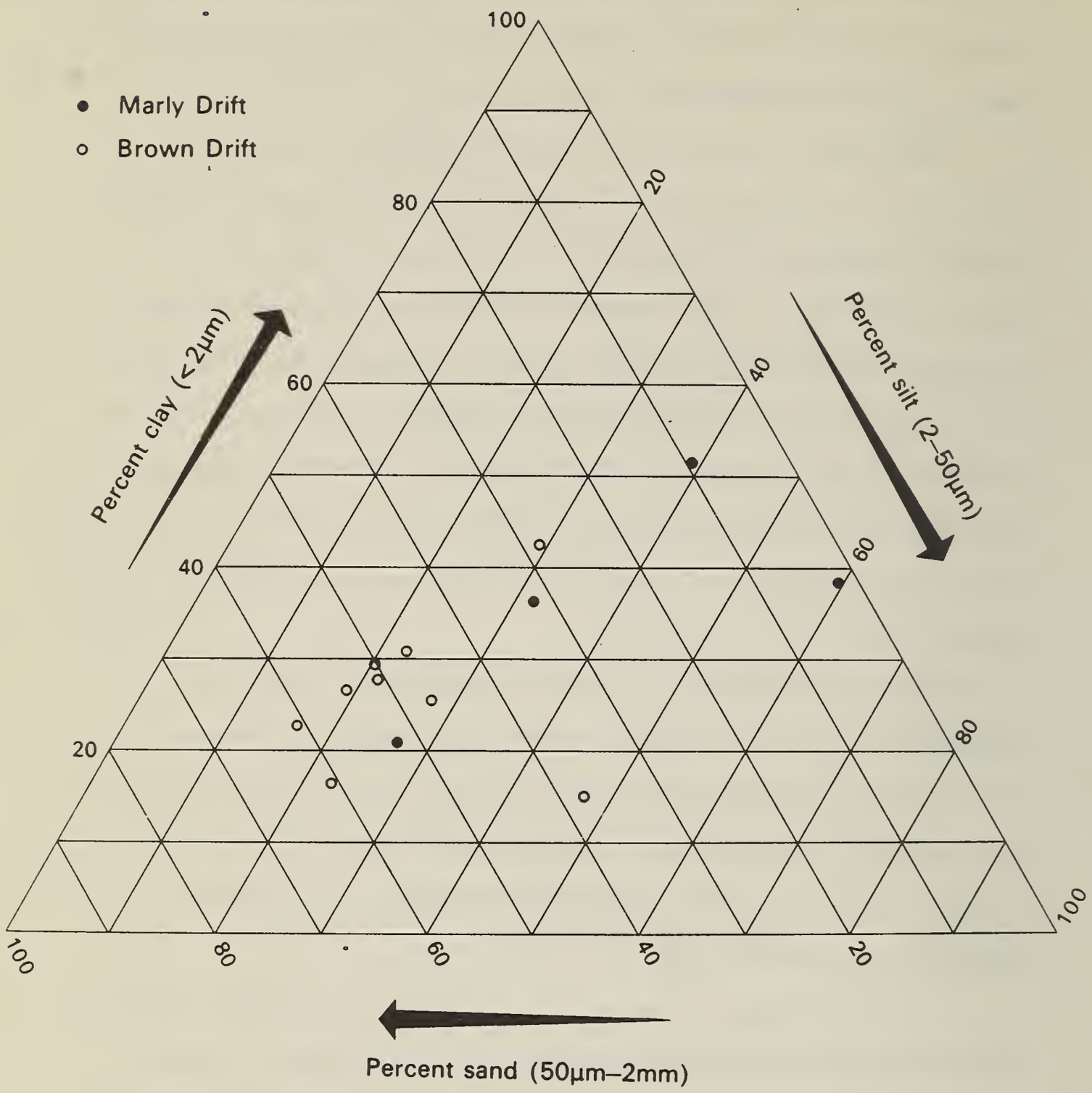

Figure 5a. Triangular Co-ordinate diagram. Brown Drift and Marly Drift (carbonate free determinations).

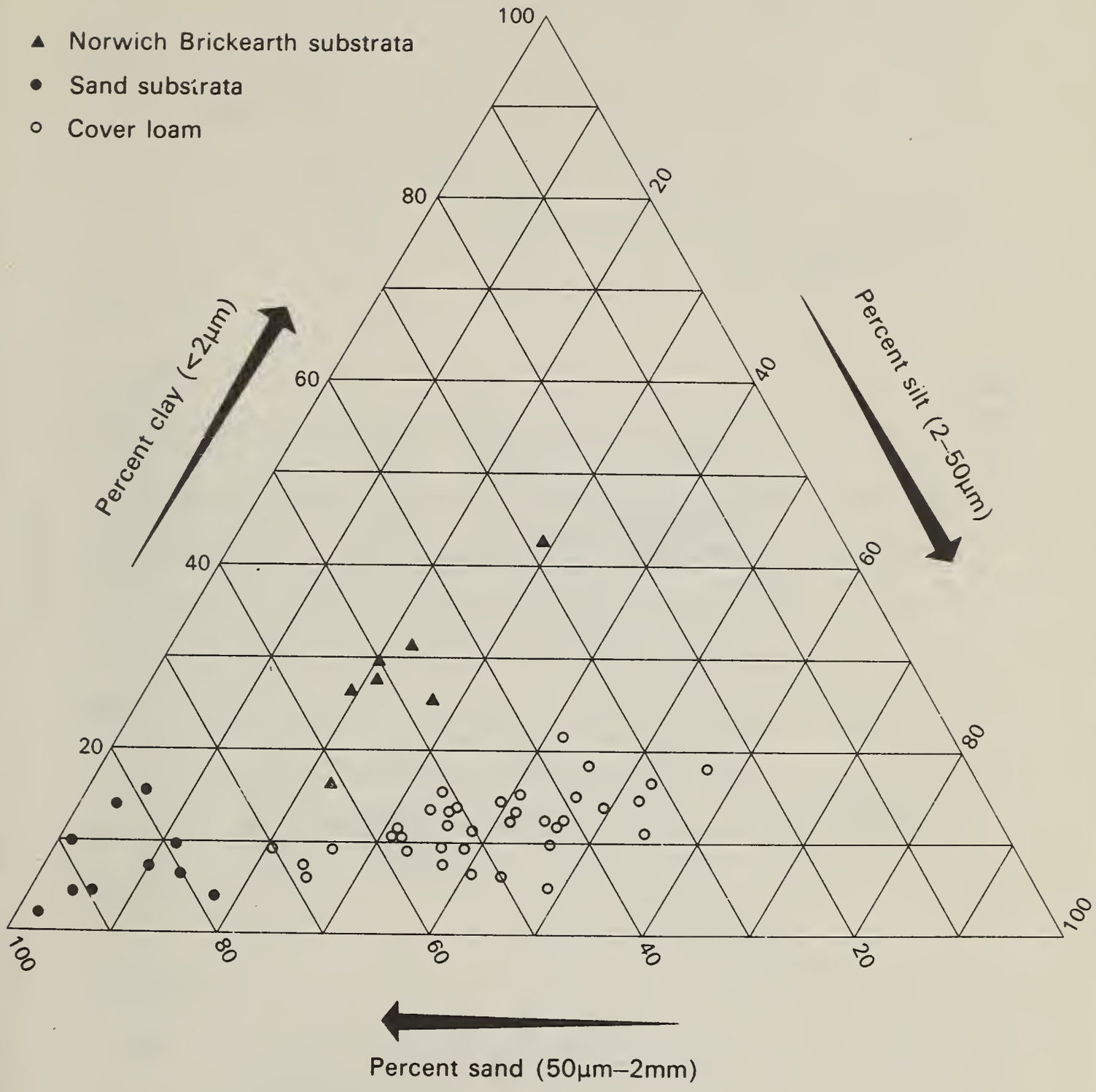

Figure 5b. Triangular Co-ordinate diagram. Cover Loam and substrata.

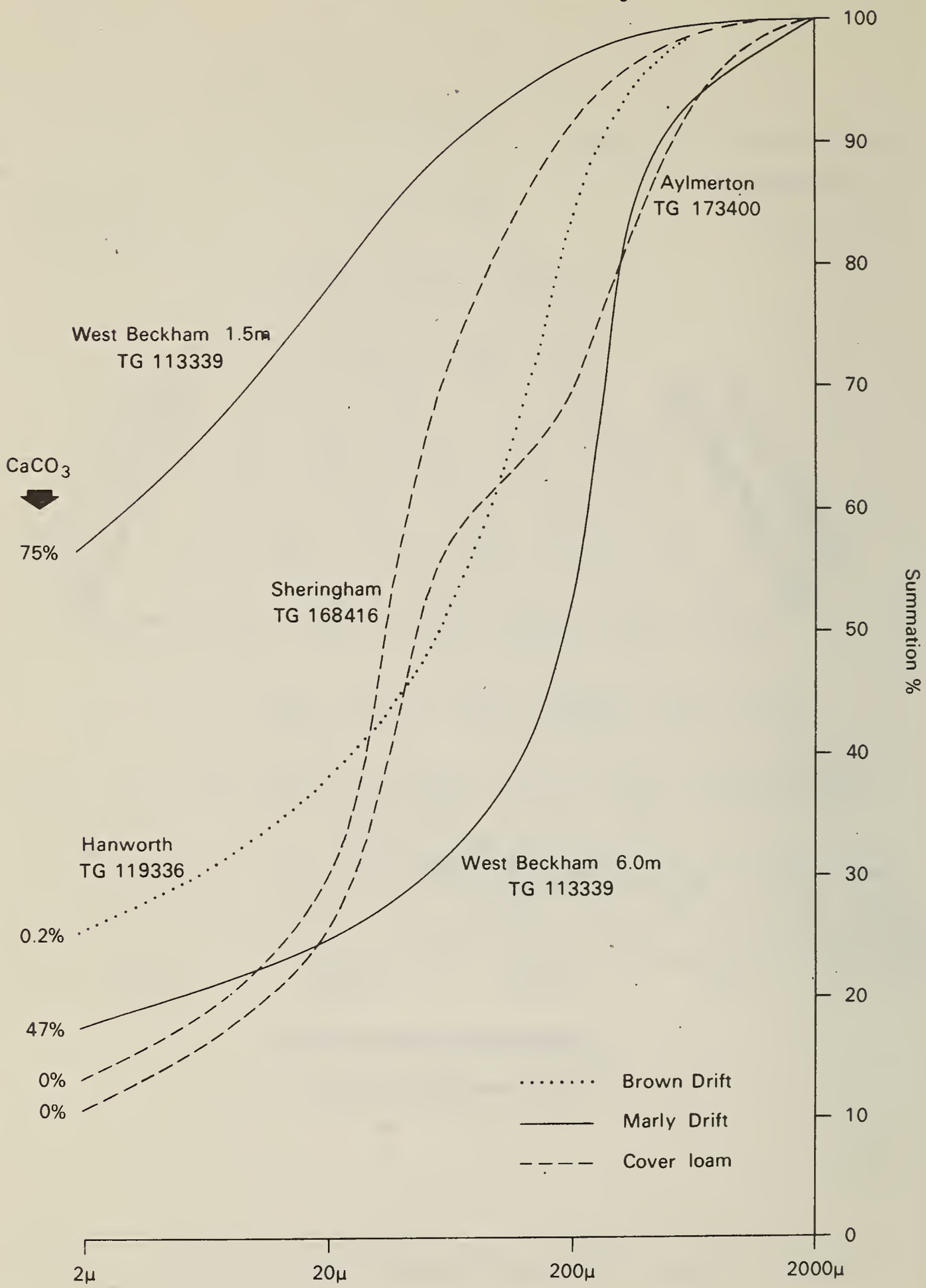

Figure 6. Particle-size distribution curves of selected Brown Drift, Marly Drift and Cover Loam (carbonate free determinations).

Soil survey is principally for agricultural purposes and in this district the most important superficial deposit forming soil is the Cover Loam. This has previously not been recognised by geologists. It is, however, the principal factor in the fertility of the area. Without this blanket of, as we believe, windborne Devensian silt, most of the land would be either dry infertile sand or intractable clay loam.

Summary

Three lithologically distinct soil parent materials were identified during a soil survey of the 135 km^2 of Ordnance Survey sheets TG 13 and TG 14. A brown drift corresponds to the Norwich Brickearth and the Contorted Drift, and a marly drift to the Marly Drift of previous workers. A thin superficial cover loam overlies outcrops of both, as well as over sands, and is regarded as being largely of Devensian windblown material. The distribution and nature of these deposits are described and related to previous geological maps.

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THE PROBLEMS OF THE HIGHWAY ENGINEER IN NORFOLK

P.F. WILKES*

Introduction

The general highway engineering problems associated with the geology of Norfolk will be discussed first. The second part of the paper consists of a number of case studies of highway schemes that have been completed or are under preparation.

Generally the highway engineer is interested in superficial deposits for the construction of embankments and cuttings. Of concern are the behaviour of the various materials in respect of stability, settlement and the suitability or otherwise of the materials to form component parts of a highway, for example, bulk fill, sub-base, concrete aggregates, etc. Where bridgeworks and other structures are involved the ability of the deposit to take the higher loadings imposed by the foundations is also of considerable interest, although in Norfolk a large number of such structures require piled foundations. In those cases a knowledge of underlying deposits becomes essential.

General problems

An inspection of the Geological Survey Map, Drift Edition, for Norfolk reveals that the deposits of main concern to the highway engineer are almost entirely Quaternary deposits. The geological history of the Quaternary deposits in East Anglia is complex. However it is the alluvial and fen deposits which create the majority of stability and constructional problems, as these are generally highly

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compressible and of low strength.

In addition to the natural features that the geological succession has provided in Norfolk - flat expanses of Fenland to the east, a generally low lying aspect to the whole county with little rapid change in elevation - artificial features can be seen which affect the deposition of new material, the most prominent of these features being, perhaps, the Broads. At one time these were considered to be naturally occurring; however, recent evidence points to their being the result of peat digging. The more recent artificial features are to be found in the east of the county and in Cambridgeshire, where large scale flood relief and drainage works have been carried out, including diversion of the Great Ouse River into man made "cuts. Gravel and other mineral extraction will also have their effect on the ultimate geological sequence in parts of the area.

Examining the behaviour of the various strata as engineering materials, it is convenient to consider these materials in two broad categories; those suitable for engineering purposes and those unsuitable.

Suitable materials are those on which, or in which, highways and associated structures can be constructed with minimum problems. There are also those which may be used for constructional materials, for example as fills, concrete aggregates and in gravel asphalt. Such suitable materials include sands, gravels, boulder clays, brickearths and the like, which generally present the engineer with few difficulties in their use or re-use. On excavation or subsequent rehandling some of the materials may require careful treatment, for instance brickearths, and to a lesser extent boulder clays, become intractable

materials during inclement weather conditions when the moisture content increases. (Conditions which invariably pertain when a job becomes delayed for one reason or another and there is no float remaining in the earthworks programme.) Alternatively during long spells of dry weather compaction problems occur with some of these materials; a further hazard in these conditions is the formation of dust clouds which without fail seem to reduce a world record for some valuable agricultural crop to abysmal failure! Generally however, the engineer can expect little difficulty in areas where these materials abound, and these virtually cover Central Norfolk.

Unsuitable materials are the alluvials and fen deposits which can be found to the west and east of the County, and also along the courses of the multivarious streams and rivers. These alluvials and fen deposits are invariably of low strength, highly compressible, and generally exhibit overconsolidated features, the latter being usually difficult to quantify at site investigation stage. By their very history of deposition they are also of a very variable nature. These materials require the use of various engineering techniques to allow the construction of highways and bridges on them. The techniques can be manyfold, for example: complete excavation, displacement, stage construction, surcharging and the use of facines. For the engineer selecting a route for a new road,a consequential problem occurs in alluvial areas. The alluvial deposits in Norfolk appear to produce either a habitat suitable for rare flora or conditions which in turn support rare fauna, for example orchids and micromoths, and therefore a number of S.S.S.I.'s (Sites of Special

Scientific Interest), nature reserves and bird sancturies exist in Norfolk. A new highway route will often cut through these or affect the conditions in such a manner that the flora or fauna are in danger of being destroyed, unless the engineer makes every effort to maintain the natural conditions on each side of the works.

A feature of the area, particularly the fenland are the 'islands' of gravels, boulder clays and the like within the alluvials, on which settlements have been constructed. Also towns and villages have usually been developed right to the edge of the more solid materials, leaving the area bounded by the alluvial deposits. Therefore any bypass route is forced onto the poor ground.

The investigation of the various strata can give rise to some concern to the engineer. Each type of material has its own inherent problems, particularly in obtaining samples. Disturbed samples present no difficulty. The problems arise in undisturbed sampling, particularly in the alluvial deposits. It has been found that the more reliable methods of obtaining parameters of the various materials are to utilise in situ means wherever possible. Boulder clays are difficult to sample because of their constitution. However, experience in their use shows that from an engineering point of view their behaviour is consistent, there is little long term settlement and no stability problem. The various alluvials and fen deposits, on the other hand, require careful handling, as the materials are susceptible to sample disturbance.

The adage "a site investigation is only as good as the quality of the sampling" certainly holds true for these materials.

The natural features of Norfolk, i.e. flat expanses of fenland, its generally low lying aspect with little variation in elevation, give rise to yet another problem for the engineer, that of provision of adequate drainage. In some areas the use of soakaway techniques is possible and in some instances deep soakaway boreholes are utilised. In others, long distance outfalls have to be constructed. A feature of the fenlands is the large scale drainage works that have been carried out in the recent past, these include the diversion of the Great Ouse River into man made "cuts" and the construction of large drains such as the Bedford Level and the Hundred Level Drains. The drainage problems are compounded by the fact that some areas of Norfolk are below sea level and drainage is by pumping, as is evidenced by the large number of windmills which were used for this purpose before the introduction of electrical power.

Case Studies

A number of schemes that have either been constructed, are in the process of construction, or at the design stage, will be described. These will serve to illustrate the types of problem that arise. The locations are shown in Figure 1.

(i) King's Lynn Southern Bypass

This has proved to be the most complex scheme constructed in the County, due to it being situated almost entirely on typical fenland deposits. The geology of the area is briefly as follows; underlying the Quaternary strata is Kimmeridge Clay, above which are superficial, or drift, deposits, consisting of glacial material, post-glacial to Recent alluvium and peat. The natural deposition of these materials has been compounded by artificial means arising from such activities

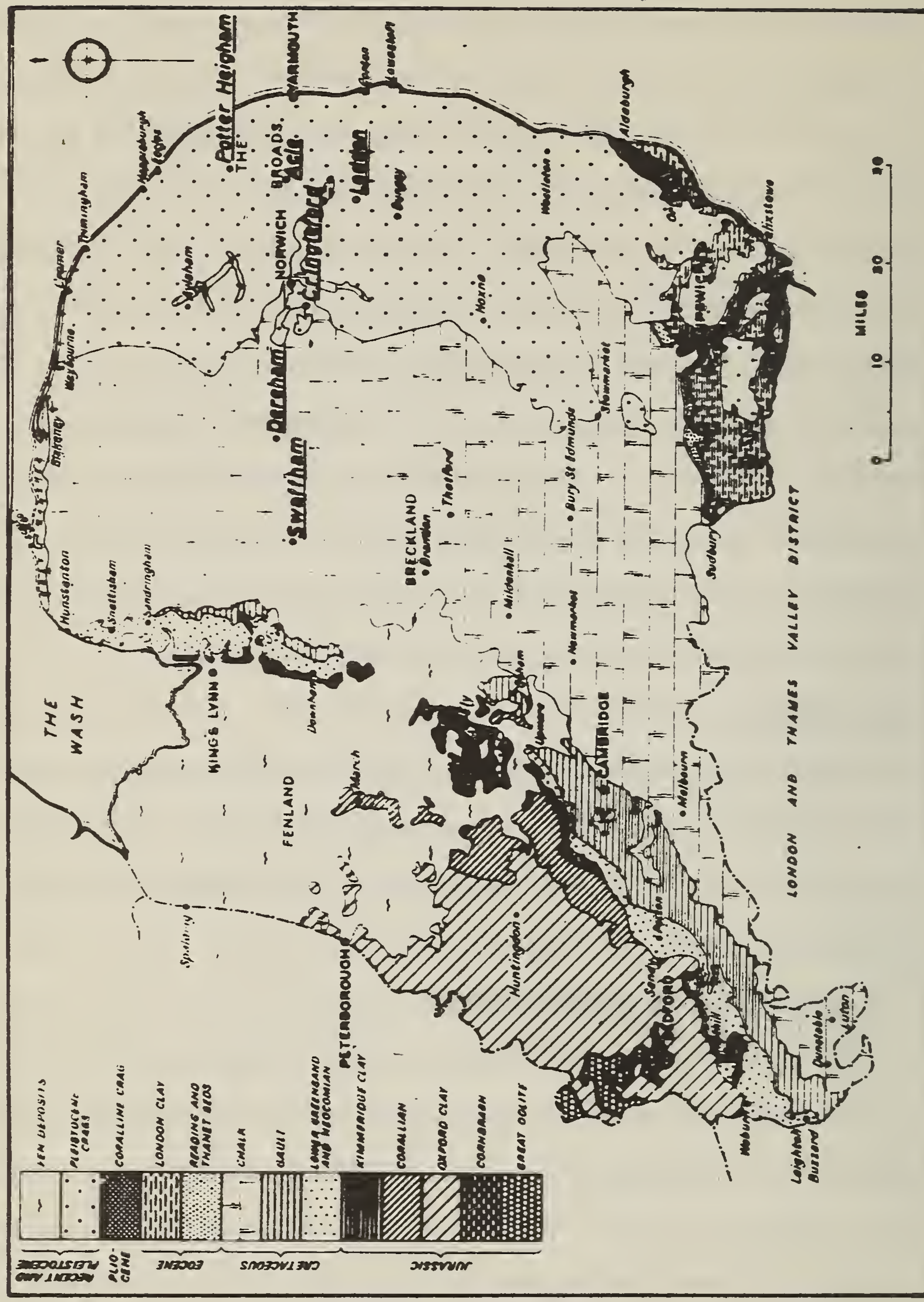

Figure 1. Location of highway case studies, in relation to geology.

as reclamation works dating back as far as the Roman era. The most recent examples being the diversion of the Great Ouse River into channels such as the Eau Brink Cut constructed in 1821.

A simplistic sequence, as revealed by boreholes, is a three layered structure consisting of finely bedded clayey silts and fine sands, fen peat, and silty and organic clays (generally soft), overlying Kimmeridge Clay. The total depth of these materials being some 13 m to the western end and gradually decreasing west to east to a minimum of 3 m. Generally the peat layer was found to be between 1.5 and 0.5 m thick, although it appeared to have been eroded away in places at some time in its history, and was generally lying at ordnance datum level some 3 m below ground level. Inclusions of glacial materials ranging from boulder clays to gravels were observed within the lower layer. The Kimmeridge Clay is generally a stiff to hard grey laminated and fissured silty clay containing shells, shell fragments and fine gypsum crystals, the latter occasionally being found in layers. Beds of bituminous clay occur, usually recognisable by their dark brown colour and waxy appearance, and bands of hard claystone or mudstone can also be found. The upper part of the Kimmeridge Clay is often weathered to about 3 metres below its top surface, the weathering being usually recognisable by a mottled brown coloration. The main effect of this weathering is a reduction in strength. Highly weathered clay showing signs of reworking was also found.

The results of the various tests carried out during the site investigation showed a considerable variation in parameters along the length of the job, to such an extent that different constructional techniques were suggested for comparatively short lengths of the

scheme. These methods included the use of sand drains, two stage construction with a long consolidation period between stages, single stage construction with batter slopes at various angles along the route, the use of berms, surcharging, removal of unsuitable material and filling adjacent lowlying areas. The major problems were associated with stability and consolidation of the low strength, highly compressible material, under the loads imposed by the high embankments necessary for grade separation. In order to test various techniques a trial embankment was constructed, a section of which was deliberately failed. The results, when analysed, led to considerable savings on the cost of the scheme. Extensive monitoring of the behaviour of the alluvial deposits was adopted during the construction and reading of the instruments is being carried on for several years yet, as there is much data to be obtained from this scheme that could be utilised in the design of other schemes. The cost of the monitoring has also been recouped several times over.

A method was developed from the trial embankment data, for giving an indication of the approach of an embankment failure. Several such indications were observed during the monitoring of the main works and filling was successfully stopped before failure occurred - except on one occasion when a localised section failed between lines of instrumentation. The method is considered to be suitable for similar soft materials.

A further complication in the design of the scheme was for the foundations of the Great Ouse River Bridge. Some 200 m upstream of the proposed bridge site a slip had occurred in the flood bank of the

Eau Brink Cut (Skempton 1945), and as the general land level of the King's Lynn Area is below that of mean high water level, the River Authority was concerned about the consequences of a failure of the river banks caused by the bridge works. Due to problems in constructing bored piles in the Kimmeridge Clay it was considered necessary to use a driven pile, which gives rise to problems of vibration during driving. As a number of the various layers found within the Kimmeridge Clay acted as channels for ground water under some considerable pressure, it was considered vibrational problems were easier to handle than dealing with water under pressure in a deep borehole (the Kimmeridge suffers from a considerable loss in strength due to softening in the presence of water). In the event this proved the correct solution, as several piles, after being driven during the actual construction, had water seeping up between the clay and the pile face. To reassure the River Authority as to the feasibility of such a proposal, a piling trial was carried out, monitored by piezometers and inclinometers. The piles were prebored to below a gravel layer within the soft alluvial deposits and the techniques used proved successful. It is interesting to note that during the main works considerable bank movements were noticed due to the tidal range. This created problems in monitoring the main pile driving which were overcome to the satisfaction of River Authority, contractor and County Council.

Compounding the problems of the earthworks was the fact that the route followed the disused line of the M. and G.N. railway, the embankments of which were of insufficient width to accommodate the new highway. Therefore problems of differential consolidation also

occurred. Bridges had to be designed to allow for settlements or special treatment given to the design of the approach embankments, by, for instance, the removal of unsuitable materials in the vicinity of the abutments or applying slip coatings to piles or the backs of abutments and wing walls.

The bypass is now open to traffic after a three year contract period and it will be interesting to see if the long term predictions of settlement, based on the trial embankment data, actually occur.

(ii) Loddon Bypass - A.146

This bypass was opened to traffic earlier this year and was constructed by direct labour with specialist sub-contractors for such items as the earthworks, fencings, etc. It lies to the south of Loddon and is some 3.75 km long.

The route crosses two streams, the River Chet and Loddon Beck. The site investigation showed sands and gravels, boulder clay, brickearths and peat, the latter being in the vicinity of the stream crossings. Whilst the extent of the peat was limited, it was of a very wet nature, which made the drilling of the boreholes somewhat difficult. Moisture contents were measured in the 400-800% range. It is these peat areas which created the major engineering problems, and it is convenient to discuss each river crossing separately.

Dealing first with the Chet crossing, where the peat was relatively shallow, some 3 m being indicated overlying firm, uniform, fine to medium sands. It was decided to divert the river temporarily and excavate the peat, backfilling with material excavated from cuttings within the site - an excess of fill was available on this scheme which is rare for road projects in Norfolk. The peat on excavation was

first spread on the adjacent marshes by the sub-contractor, who soon found this was impracticable due to plant getting bogged down. The peat was then spread on adjacent fields higher up the valley sides with no problems. It is interesting to note that notwithstanding the nature of the material a surprisingly dry excavation was obtained with near vertical stable faces. The excavation also revealed that the surface of the underlying sands had a relatively steep dip to the downstream side of the excavation, a maximum depth of some 6 m of peat being encountered. The backfill consisted of an uniform sand, which was later re-excavated for a bridge crossing the final course of the Chet. By the time the re-excavation occurred the water table level had reinstated itself to just below the original ground level. This coupled with the grading of the sand gave rise to quick conditions occurring during excavation, and it became necessary to construct a cofferdam around the bridge site which required constant pumping. On the occasions when pump failures occurred the cofferdam rapidly filled with water.

Loddon Beck, on the other hand, presented different problems. Here the peat was much wetter than the Chet valley, in the 700-800% range, and much deeper, up to 15 m. It was considered at design stage that it should be possible to displace the peat easily. The procedure was to excavate down to the underlying firm material, where this did not exceed 3 m, and elsewhere excavate 3 m, replacing the excavated material with spoil from the cut areas. This method proved satisfactory until the firm base was more than 3 m, when problems arose due to uplift of the base of the excavation under the weight of placed fill. This uplift also revealed large quantities

of silt that had not been detected in the site investigation. Excavation of the peat ceased, and fill was placed directly on the original ground surface, keeping the slightly firmer crust intact for constructional purposes. This method created one or two localised problems, considerable heave of the original ground surface, equal to the height of the new embankment, occurred a few metres away from the main area of the works. This heave took its toll on the existing drains adjacent to the works, which necessitated remedial action to maintain drainage flows across the new road line. The final course of the Beck was amended from the design to allow an Armco culvert to be constructed in a position where the level of the firm underlying material was known. Again quick conditions occurred during re-excavation of the deposited uniform sand. The embankment was constructed to just above its final level, and tell-tales on the original ground level showed that this settled a maximum of 5½ m in the first 3½ months during construction. The embankment was surcharged about six months later. The delay was due to constructional problems. Unfortunately it was only possible to maintain surcharge for about 3½ months, but during this time a further 3.5 m of settlement occurred, and settlement of the finished road is still occurring, albeit at a decreasing rate (150 mm in 8 weeks at end of 1975), and it is anticipated remedial works will ultimately need carrying out to re-instate a smooth curve to the vertical alignment. During construction of the embankment a longitudinal crack about 30 m long occurred overnight, and one half of the embankment was found to be some 750 mm below the other half. What was described appeared to be a circular arc type failure, but the site staff felt that it was due to

a failure of the stronger crust, and carried on filling in view of the fact that a displacement technique was being used. In the event no further problems arose.

The brickearth caused problems for the earthmoving contractor as he chose to attempt to move it after a particularly wet spell, which was unavoidable, as all slack in the earthmoving programme had been used up. The natural moisture content of the material found during the site investigation was of the order 17-19% with a plasticity index 15 to 17.

(iii) Cringleford Bypass

This is a bypass of the A.11 on the outskirts of Norwich. The sequence revealed by the site investigation comprises Chalk, overlain by Crag deposits consisting of gravels and sands. The River Yare traverses the route, and associated with the river valley are alluvial deposits and peat. The problems associated with the construction of an 8 m high embankment on these latter deposits were overcome by excavation, and replacement by true free draining material excavated from the adjacent new Broad on the U.E.A. campus. This material was also used to make up the shortfall in the cut and fill balance.

Generally, few problems associated with the Quaternary deposits occurred during the construction of this bypass, although in the Crag deposits of the west bank of the river valley quick conditions arose in the construction of deep trenches for a replacement sewer. The deposits in this area were an almost uniform fine sand, and a natural high water table level was encountered. This problem required close sheeting and only a single pipe length of trench open at any one time.

It was necessary to relay an electricity main cable across the

new route at an early stage of the contract, and as that section was ultimately in cut, a 9 m deep trench was excavated with battered sides. This was in the Crag deposits, and it was interesting to see a virtually perfect grading of material from coarse gravel at the top of the excavation to a very fine sand some 9 m below.

The Chalk, as found at Cringleford, presents some problems for the engineer. The Chalk is a very soft material, with a moisture content at or very near its saturated moisture content. This makes the material difficult to sample and to subsequently rehandle, as the material behaves in a thixotropic manner, and in sampling becomes further remoulded. It is considered that during the geological history of the Chalk extensive restructuring has already taken place under glacial action, either by frost action or even by complete redeposition. The slurrying-up that occurs when the chalk is being worked as a fill material gives rise to delays, unless the material is kept at a moisture content below its saturation point. Problems also occur during pile driving, as the dissipation of the driving energy activates the thixotropic nature of the Chalk, and it is not possible to drive piles to a set depth. A suitable length for the pile has to be determined by pile tests and experience. The Chalk also contains flint nodules which give rise to minor problems.

(iv) Potter Heigham

Potter Heigham bypass was constructed in 1969, as part of a 6 mile long improvement, which for most of its length utilised the disused M. and G.N. railway line.

At Potter Heigham the bypass crosses the Thurne Valley, and, as

part of the preliminary investigation, a trial embankment was constructed to test the in situ performance of the foundation materials. The site of the trial length of embankment was to the east of the river, where the line of the disused railway diverges from the line of the bypass. Here the strata consists of 10m of soft grey silt, overlying 1 m of fibrous peat, which in turn overlies dense sand and gravel. Instrumentation was confined to three sections, each with six piezometers placed at various depths in the silt, with one plate settlement gauge on two of the sections. To enable an estimate of differential settlement to be made, one gauge was placed on the line of the railway embankment, and the other on virgin ground. Prior to the commencement of filling the old railway embankment was bulldozed away and spread on the adjacent marsh. The rate of filling was controlled to maintain a ratio of pore pressure increase to total stress increase of 0.55, calculations having indicated that this was desirable to achieve a factor of safety of 1.5 Filling ceased at a height of 3.6 m when a longitudinal crack appeared along a line ocincident with the junction of the two embankments, this was seen to be due to differential settlement, as there was no heave evident at the toe of the bank. The estimated settlement after 22 years was approximately 0.43 m, readings on the settlement gauges showed 0.18 m and 0.55 m respectively after 13 months.

(v) East Dereham

This scheme is at tender stage so it will not be possible to give a full picture. It is included in this paper to give an indication of possible pitfalls to the design engineer. The major

deposits indicated on the geological drift map are boulder clay, overlying Chalk, with a few isolated alluvial areas associated with streams. Knowing this there could be a tendency for the main investigation to be confined to the alluvial areas, with a cursory inspection of the boulder clay deposits. However, the site investigation revealed that, on the site of a major bridge, artesian conditions occurred, with a head of at least 3 m above ground level. A second bridge site is also affected, to a lesser extent, by artesian conditions, and the embankment level was raised to overcome any problems.

A problem associated with the alluvial deposits, at a place known as Scarning Fen is, as mentioned in the Introduction, the formation of a suitable environment for rare flora and fauna. The Fen is a site of scientific interest, being the habitat of Bryophytes - mosses and ferns. Fortunately the route of the bypass only crosses the northern boundary of the fen, where it is the home of old prams and bicycles. The problem here is the construction of an embankment which does not affect the natural drainage of the area, and the design of a road drainage system which will not allow pollution of the fen. The first objective will be achieved by the excavation of the fen material, which at the point of crossing is relatively shallow, and this will be replaced by a free draining material. The highway drainage problem will be covered by a carefully designed and constructed closed drainage system.

(vi) Acle Slough

Immediately to the East of Acle village the A.47 trunk road crosses

an area of poor ground known locally as Acle Slough, which is largely an active peat bog. Trouble has occurred for many years, over a length of 240 m, necessitating frequent resurfacing to remove irregularities. The strata consist of approximately 12 m of peat overlying a mixture of sands, sandy clays, silts, etc., with what is though to be Crag deposits at approximately 20 m below ground level.

In December 1963 considerable undulations appeared in the road surface, which was immediately made up to level with 1600 mm of crushed concrete and surfacing. Throughout the next six months similar treatment, including making up the verge which was sinking more than the carriageway, was carried out at approximately monthly intervals to remedy the continuing failure which affected the southern half of the carriageway. Settlements of the order of 0.25 m were commonplace.

In October 1964 an inspection revealed that what appeared to be a reasonable road surface was merely a crust approximately 250 mm thick, and beneath this was a crack with a top width of approximately 450 mm and extending to a depth of approximately 5 m. Making up continued at intervals until late 1965 when comparative stability was achieved. It is estimated that a total of 7 m of fill was placed on the verge during the operations, all of which disappeared into the peat.

In 1972 10 inclinometers were installed alongside the road to a depth of 20 m, and pins driven into the road surface and levelled, in an effort to detect any pattern of movement. Monitoring ceased in 1974, when it was concluded from the results so far obtained, that no real pattern had emerged. The scale of deflections obtained from

the inclinometers was small, and in some cases were within the accuracy of the techniques used to survey the tops of the tubes at each set of readings. The length continues to be resurfaced at intervals to remove irregularities that still appear.

(vii) Acle Bypass

The route of the proposed bypass, which passes to the north of the village can be conveniently divided into 3 distinct topographical areas namely west of Fishley Carr, Fishley Carr and the Flood Plain of the River Bure.

West of Fishley Carr there are two areas of low fill, a shallow cutting, and the main cutting which attains a maximum depth of 12 m. The soil conditions over this length show great discontinuity over short lateral distances. A capping of boulder clay conceals sands, sandy clays, and at depth (30 m below highest ground level, 18 m below O.D.) the dense grey silty sands of the Crag deposits were encountered. The engineering problems associated with this area are confined mainly to the possibility of local seepages in the face of the cutting, and the fact that some of the clayey sands constitute marginal fill as defined by the Department of the Environment Specification for Road and Bridge Works, i.e. natural moisture content exceeds plastic limit x 1.2.

Fishley Carr is an area of soft amorphous peat (natural moisture content 710%), varying in thickness from 2 to 10 metres, overlying 5 m (maximum) of very soft silty clay. Crag deposits were encountered beneath the silty clay. Here the water table is at ground level, and as the Carr is an area of scientific interest, the Nature Conservancy

have asked that the level of the water table remains unchanged. At the present time the intention is to displace the peat by surcharging the embankment, which is to be of free draining granular fill.

East of Fishley Carr, the route crosses the Flood Plain of the River Bure until it rejoins the A.47 east of Acle. Throughout this length the soil conditions are fairly consistent, being approximately 18 m of soft silty clays overlying Crag deposits of dense grey silty sands. A layer of amorphous peat, (natural moisture content 415%) occurs between levels of approximately 5 m and 7.5 m. Recent shallow boreholes along the line of the A.47 confirm the existence of the peat layer to within 1 mile of Great Yarmouth. The low shear strength and high compressibility of the silty clays give rise to the main engineering problems on the scheme, those of stability and settlement.

Preliminary settlement calculations have indicated that up to 0.6 m of settlement could occur under a one metre high embankment. Values of m_v and more particularly C_v show a degree of scatter, and the magnitude of settlement, and the time for it to take place, remain uncertain. Further investigations are being made, since the time factor concerned can obviously affect the contract period chosen. Stability analyses based on <u>in situ</u> vane strengths (mean c_u, 10 Kn/m^2) show that a maximum height of embankment of 2 m could be achieved using common fill and 1 on 2 side slopes. The intention, therefore, is to keep the embankments as low as possible (maximum height 2.5 m) and to use light weight fill in selected areas. Because of these problems a 220 m long viaduct will be required to carry the A.1064 over the bypass.

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NORFOLK SANDY BEACHES: APPLIED GEOMORPHOLOGY AND THE ENGINEER
(a summary of the Presidential Address for 1975, delivered 13 October 1975)

K.M. CLAYTON*

Introduction

The coastal zone of Norfolk is geologically the youngest feature of the County, and certainly the most active. We may estimate that 95% of the solid material eroded each year is lost by marine action, and even if we include material carried by the rivers in solution, the coastal share of total denudation is about two-thirds. We know almost nothing about the early stages of the Flandrian transgression, but the coast owes almost all its features to the changes of the last 5-6000 years when the sea has been very near its present level. The sea has, of course, been acting on a land with its own pattern of geology and relief, and the general outline of the coast, together with the occurrence in the coastal zone of relatively high or low land, is a function of the geological (and geomorphological) history of the land itself. Nevertheless, the Quaternary deposits of Norfolk are rather easily eroded by wave attack, and the coastline has moved relentlessly landward at about 1 km every thousand years in some areas, while elsewhere a belt of marshland and dunes up to 3 km wide has been created. In terms of area, the long term gains have more than balanced the losses, partly because far smaller sediment volumes are involved in the building up and out of coastal marshlands than in the destruction of high cliffs.

Worldwide, we have some evidence that the dynamic equilibrium

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characterised by modest rates of coastal change, appreciable areas of long-term equilibrium, and a general predominance of land gains over land losses may be coming to an end. Three factors are involved: 1. the past 6000 years have probably seen the natural reclamation of many of the really shallow coastal areas, and further outbuilding of sediment will be slow or absent as deeper water is reached; 2. at present sea-level is rising at about 1 - 1.5 mm/year, and this encourages erosion and partially affects the building up of marsh levels; 3. in the last century or so there has been a great deal of interference with the natural systems by engineers, and in so far as they have been able to reduce coastal erosion they have affected the natural sediment balance of these coasts. It would be difficult to determine the relative importance of these three factors, but in combination they are leading to appreciable departures from the dynamic equilibrium of the past 4000 years. We need to add a fourth consideration to the context in which we view the coast as applied geologists, and that is the dramatic change in the number and the expectations of those who choose to live in the coastal zone.

Until 150 years ago no-one lived near the coast who did not have to, and they appreciated the hazard of their situation, usually adjusting to settle on a relatively high, and hopefully stable, piece of land. Increasingly, as the last few decades have gone by, more and more people have chosen to live near the coast, either in connection with the holiday trade or perhaps for retirement. This new settlement has colonised many areas liable to coastal flood or threatened by coastal erosion. Either the hazard has been unappreciated, or the assumption

has been that a technologically advanced country has the ability to defend us all against the ravages of the sea. We must examine this assumption to see whether it is a reasonable and tenable view of coastal defence in the last quarter of the twentieth century.

The process-response system at the coast is a short-term one with very different relationships to those normally the concern of geologists. It is possible to measure environmental variables over very short periods of time and to observe the immediate response of the beach sediment to a single breaker, or a single tidal cycle. This gives us the possibility of coming, in time, to a full understanding of the relationship between the energy inputs from the waves and currents of the sea, and the response, and thus the long-term changes of the beach system. This approach may involve the detailed measurement and time-consuming analysis of the breaking forces within a single wave, as is being studied by the Institute of Oceanographical Sciences. It may be tackled on a longer time-scale by generalising the 'weather' of a train of waves to the wave climate as it varies from one season or year to another, and along the coast with the variation of aspects (exposure) and offshore water depths. Both time scales are a legitimate basis for investigation, but the cause-effect relationships in each are very different. Since erosional problems that concern local authorities (or householders), and which are the traditional concern of coastal defence engineers, are measured in years or even decades, our own (practical) interest in the coast has involved studying relationship relevant to such time-scales.

Coastal changes and sediment movement

Although the coast, or parts of it, are undergoing continual and often rather substantial change, we possess remarkably little long-term data. The main source of information has been old maps, and where these have been carefully surveyed (effectively since the introduction of the six-inch, 1:10,560, scale in 1880) they give us information on the total retreat or advance of the coastline. Resurvey has been infrequent (although less precise revisions have been more common), but since 1945 air photography has been used on a regular basis and for any actively-changing coastal area there are usually at least two or three sets of photographs of great value for monitoring change, although several may be of lesser value through being taken near to high water. Survey of beach profiles has been limited to occasional research projects or to particular occasions when coast defence works were being planned. Attempts to measure sediment movement have been even more infrequent, and we have hardly any cases where a complete sediment budget involving onshore-offshore movement as well as littoral drift has been measured. There is no doubt that the design of coast defence schemes is disadvantaged by this paucity of historical data, and it is impossible to acquire it in the short period allowed for the planning and installation of new coast defence works. One of the objects of our current research is to acquire a run of such data and to establish the feasibility of setting up a beach monitoring system.

The contract from the Department of the Environment requires 82 beach profiles to be surveyed every three months. These give us

a good deal of information on seasonal and longer-term changes in beach volume, and should also allow a selection of significant profiles to be made that can be surveyed on a continuing basis, hopefully by the responsible local authorities. In addition we have attempted to calculate littoral drift of sand through the beach by using volunteer observers to record the height and angle of approach of waves. Coupled with a check (by using fluorescent sand as a tracer) that the American empirical formulae apply to Norfolk beaches, these data have allowed computation of littoral (sand) drift values for eight sections of the East Anglian coast. From these values an initial, and still unsubstantiated model of coastal sand transport has been produced (Figure 1). We are currently examining these data further and comparing them with estimates derived by other methods.

We may pause here to note that the model excludes both mud and shingle. McCave has recently discussed the mud budget for the North Sea. About 1/3 of the sediment contributed from erosion of the Norfolk cliffs (i.e. about 250,000 m^3/yr) is mud, and this is quickly moved away by tidal currents. No drifter releases have been tried from the area offshore of these cliffs, but it seems most likely that the mud that does not move offshore into the North Sea 'sinks' is deposited in the estuaries and on the marshes of the Essex coast. Mud accumulation in the Wash is not large (and may be in part the result of local redistribution), and drifter movements suggest that it may come from the Holderness cliffs rather than from N.E. Norfolk. Rates of mud accumulation around the Norfolk coasts have not been measured very carefully, but if the North Norfolk marshes were simply to keep

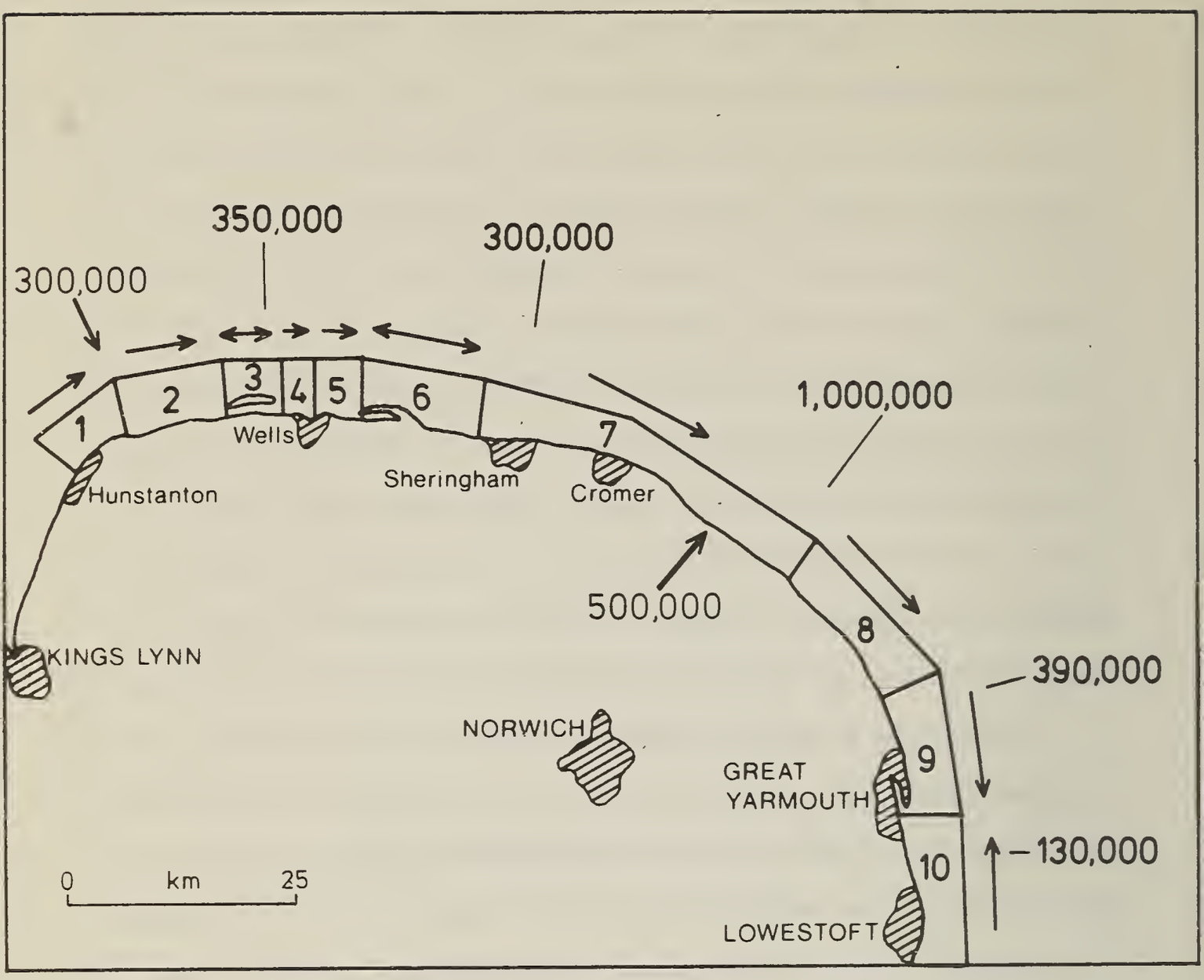

Figure 1. A model sand budget for Norfolk beaches (after Cambers). (Values in cubic metres per year)

The system suggested here has two inputs: from offshore in the northwest, and from the eroding cliffs. Computed net rates of movement for five points are shown. Offshore movement is not quantified but is implied by the littoral drift values and will be located at the cell boundaries shown.

pace with rising sea-level, the annual increment would be of the order of 100,000 m^3.

It has often been suggested that most of the shingle along the coast was placed in position by converging wave trains as the Flandrian transgression worked across the continental shelf. It is of course still reworked by contemporary waves and currents as the migration of Orford Ness shows, but this concept suggests that contemporary supply is not an important feature in the maintenance of these shingle beaches. In Norfolk the most important of these features is the long shingle ridge from Weybourne Hope to Blakeney Point. This ridge is slowly being moved landward by wave action at just under a metre each year on average. Its form, with the spit at Blakeney, suggests westward transport from the cliffs at Weybourne and beyond. The wave observer data of 1974/5 strongly support a net eastward transport of sand along this section of coast, and it has been suggested that the balance of the higher energy waves required for significant shingle movement might shift the shingle in the opposite direction. However, recomputation of the data using a reasonable threshold value shows that even considering the higher energies alone, net drift movement will be eastward. Thus Blakeney Point may be attributed to the realignment of an existing shingle beach and the landward movement of the eastern end to match cliff retreat; it does not fit the textbook version implying littoral drift towards the point. Such eastward drift as has occurred has no doubt aided rotation of the ridge towards a position more nearly normal to the beach-forming waves, and as the ridge rotates in this way, the rate

of littoral drift will decrease. Present rates for sand are quite low, and are probably very low for shingle; indeed were this not so the feature could hardly have survived so long.

Three natural environments

Three almost natural areas of coast have survived in Norfolk, two because they are accreting, one because until recently it was too costly to defend. These areas have particular interest simply because they are continuing to evolve geomorphologically and geologically with little interference by man. Indeed it is worth stressing that to the geologist and geomorphologist the naturally occurring processes of the coasts are as worthy of protection through such devices as nature reserves as are rare plants or birds. Indeed it is hard at present to see how else an eroding coast might be preserved, while even accreting beaches in natural condition are increasingly restricted to coasts preserved from development for quite other reasons. Since many of the features of special interest in such reserves are connected with the instability of the natural environment, it is clearly important to preserve all aspects of that environment from improvement or development by man.

1. The barrier island coast of North Norfolk

Exposed as it is to the relatively long fetch from north to south down the North Sea, this is a high-energy coast, rather closely adjusted to wave attack, both in profile and plan. The coastal zone is backed by an abandoned cliff-line and in front of this lies a broad zone of marshes intersected by a series of tidal creeks and more open bays. On the seaward side, beaches locally backed by dunes

break the wave attack at high tide, especially on the outer promontories and on Scolt Head Island. Between these, and locally in front of them, are very broad areas of intertidal sand. The marshes have grown up in the quieter environment behind these beaches: levels are generally low, and only at Holkham have appreciable areas been reclaimed. The cliff has not been dated, but it is possible it dates from the last Interglacial, like the related feature in Lincolnshire. It is unlikely to be related, except in local detail, to the present stand of sea-level, for that would have quickly built a series of offshore bars and barrier islands, from which the present coast has evolved. These features are still rotating into a position normal to wave attack, as is shown by the exposed marsh clay on the beach on the eastern end of Scolt Head Island. However, it is also clear that taken as a whole the coast is almost stable, and at localities such as Holkham Bay, progradation is occurring. Present changes are best interpreted as a gradual simplification of the coastal plan, increasingly possible as deposition reduces the flushing volume of the tidal creeks and embayments. While the orientation of the coast will eventually be controlled by wave attack, its position forward of the abandoned cliff line reflects a shallow nearshore zone on which the sands and marsh muds are lodged. We have no knowledge of the geology of this shallow ledge, and it could be of Chalk or of till. It deserves investigation.

Most of this coast is little developed, and planning controls and protective ownerships are likely to keep it this way. In addition, since most of the coast is stable or even prograding slowly, there is

no pressure for large-scale interference with beach processes. Nevertheless, isolated areas of erosion or flood-hazard do occur, as at the (1953) breakthrough on Scolt. Although some piles have been driven into the beach at the breakthrough, and some attempts have been made to promote dune growth, the situation is still nearly a natural one. As far as flood hazard goes, the marsh perimeter banks landward of the channel that separates Scolt Head Island from the mainland are the real protection and these are not threatened even on those rare occasions when the sea is high enough to split the island in two. Wells Beach is a local problem related more to the scour of the channel at its foot than to the general nature of this coast. It is a sad commentary on current skills in coastal engineering that a beach with so much intertidal sand in front of it should be so poorly nourished. The Salthouse shingle bank inevitably leaks at high tide and is liable to be breached during a surge: so far it has not been thought cost effective to improve it in any way.

One further feature of the North Norfolk coast deserves further examination. Although there are sizeable dunes at several points, there are other areas (e.g. Holkham Bay and Bob Hall's sand at Wells) with very wide intertidal areas of sand backed by quite modest lines of dunes. These are not attacked and rebuilt with any frequency, so one is led to conclude that the rate of sand supply is low; somewhat surprising in view of the huge areas exposed with each tidal cycle. No measurements have been made, but it does seem that these sands are rather slow to dry, either because of their

grain size distribution or because of a high water table. Indeed, it is possible to envisage a situation where dune volume could aid in the maintenance of a high water table on the beach and thus inhibit continued dune development. Whatever the reason, these relationships again underlie the overall stability of this low coast, despite its exposure.

2. The cliffs

From Weybourne to Happisburgh and beyond, almost the entire coast is cliffed. Short sections have long been defended, especially at Overstrand, Cromer and Sheringham, but it is only in the last year or so that a start has been made on defences below the high and active cliffs between Trimingham and Cromer. Measured rates of retreat on these cliffs show mean values of a metre or so a year for the past 100 years or so, and we have no reason to believe that similar rates have not been a feature of the 6000 years or so since sea-level reached its present stand. In addition retreat rates are independent of cliff height. While the immediate cause of removal of material from these unstable cliffs is wave attack at the cliff foot, continued recession through 5 or 6 kilometres can only come about through an efficient system of sediment transport and the gradual lowering of the entire offshore zone. In periods of rising sea-level, as at the present, offshore lowering may be matched or exceeded by the annual sea-level rise, but it remains a factor in the maintenance of erosion rates over time.

Man's perception of this erosion and his understanding of the reasons for it have not been very satisfactory. Few people who

live near these cliffs understand that despite the obvious signs of failure where springs emerge, the sea is the ultimate cause of the problem. One householder, driven out of his house by a huge slip that took half of his front lawn, told a reporter that "it could not be the sea causing the erosion because all the falls were at the top of the cliff". Even the local authority, unsupported by central government funds, has spent appreciable sums attempting to drain the sediments that outcrop in the cliffs. They may steepen the cliff and so gain a few years' breathing space at the top, but they will not affect the inexorable attack of the sea at the foot. As Dr. Cambers has shown, these cliffs contribute an annual average of 700,000 m^3 of sediment to the beach, 500,000 m^3 of it sand and shingle. While some must move offshore, a high proportion moves through the beach system where net littoral drift reaches a million cubic metres a year from N.W. to S.E. Here is the efficient removal system that we guessed must be the concomittant of sustained retreat. Whatever the height of the cliffs, this littoral drift can dispose of the sediment supplied with an efficiency that more than matches cliff retreat. Indeed we are driven back to the hypothesis that the ultimate control on the system is the offshore slope since this is the overall control on the wave energy that may reach the cliff foot.

Coast defence in such a situation, unless it can increase beach volumes, is unlikely to succeed for long. Indeed, any reduction in the rate of cliff retreat (and this has already occurred from Mundesley to Happisburgh) by decreasing the volume of sand and stone

delivered to the beach will produce feedback by reducing beach volumes and so stimulating erosion. Yet by attempting to stand firm at such sites as Overstrand, Cromer and Sheringham, a defenced headland, undefended bay type of coast has already been initiated, and that too cannot be stable for long. Finally, we may note the interest of geologists and soil mechanics experts in the continued availability of actively eroding cliffs, both for the exposures they reveal and the slope failure forms they demonstrate so well. Resolution of these divergent interests will not be easy.

3. The Nesses

At several points along the East Anglian coast gentle promontories nose eastward into the North Sea. These low sandy features, often backed by a complex dune belt, are known as nesses. In Norfolk Winterton Ness and Caister Ness are our only two examples, the latter has migrated southwards to Yarmouth North Beach. At Winterton the dunes and broad beach lie in front of a fifteenth century cliff, so we have some idea of the rate of accumulation, while at Yarmouth North Beach progradation has averaged almost 2 m a year since 1935 and is still continuing. Over the years many theories have been put forward to explain these features, most of them involving sand moving onshore from the offshore bank systems, under the influence of waves and tides.

Whatever refinements and corrections still need to be made to the model of coastal sediment movement that was built up from the wave observer network of 1974/5, the data are good enough to suggest a radically different interpretation of the East Anglian ness

features. It is observed that the computed value of littoral drift north and south of each ness feature is rather different. The different values result from the observed pattern of wave height and direction of approach to the shore,but it will at once be seen that the contrast north and south of each ness is to be anticipated as the effect of the difference in overall beach orientation. Since this part of the coast is already very oblique to any high energy waves coming down the length of the North Sea, the pattern is for drift north of the ness to be towards it, and of a higher value than the continuing drift away from the ness to the south. Thus as Dr. Cambers has suggested, each ness represents a cell boundary in the beach sand transport system, with higher values towards the ness and lower onward values beyond it. While the difference in these two values is available as sand feed to increase the size of the ness, in practice quite a small proportion is added to the ness and over 90% of the feed is lost offshore. Thus these nesses are shown to be zones of offshore removal of sand, and points at which sediment is lost from the beach system. We do not yet possess good enough techniques to measure the direction, let alone the amount of this offshore movement, but only offshore removal is consistent with the data we now possess on littoral movement (Figure 2).

Figure 3 gives the change in the length of defended coastline over time. If we assume that the North Norfolk coast will remain a natural area, it is clear that we are rapidly approaching the point where the whole of the rest of the coastline will be defended. In

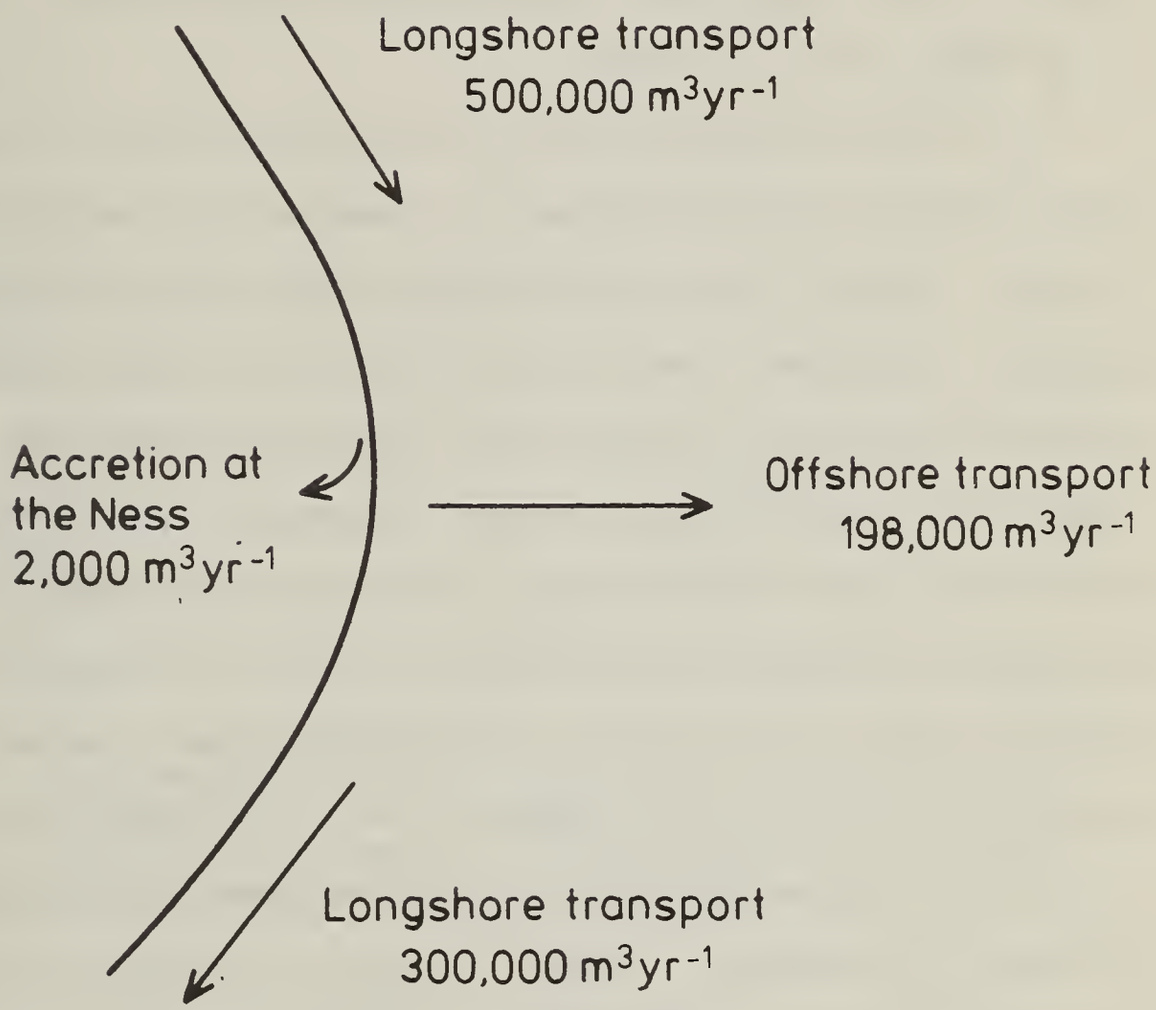

Figure 2. Hypothetical model of sand movement at Winterton Ness (after Cambers).

most cases this will be by engineering structures placed on the beach: concrete sea walls, groynes, and wooden wave breakers. Responsibility for these is divided piecemeal, formerly into even more authorities than now, but even today the responsibility for coastal defence is shared by the three coastal Districts of Norfolk and the Regional (Anglian) Water Authority. There has been no grand design: Norfolk's sea defences have just 'growed'.

It is not my purpose here to discuss the efficacy of these various forms of coastal defence, let alone the costs and benefits involved. Instead I wish to view them as intrusions into a mobile geological landscape. They intrude of course as visible objects. A few graciously-curved sea walls apart, they win no prizes for design. Indeed if the sloping wooden barriers designed to break the force of the waves before they reach the cliffs were sited anywhere else in the natural environment there would be an outcry. Not only do they intrude visually, they obstruct physically and greatly reduce the pleasure of wandering across a beach at will. Yet they also intrude, as of course they were designed to, into the dynamic system that is the coastal environment. Littoral transport is reduced, and increased erosion may ensure downdrift, as happened at Gorleston Beach when the Yare training walls were improved, and happened in turn at the Old Yarmouth Borough boundary where the Gorleston groynes ended. Even more serious is the potential impact of even a relatively short-lived cessation in coastal erosion. A glance at the model of sediment transport we have built up shows only two inputs to the system. One of these is assumed as necessary to balance the model and is from

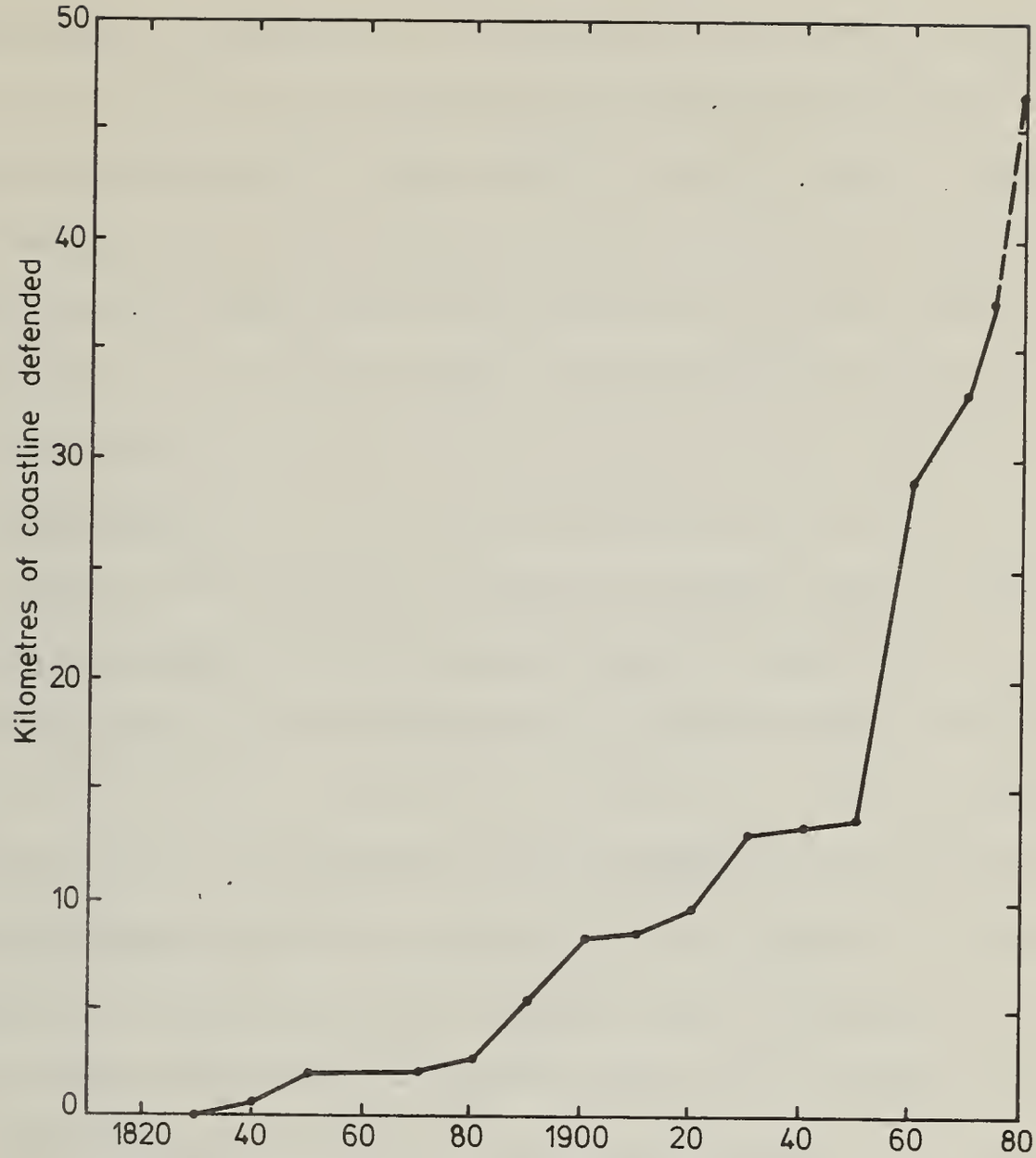

Figure 3. Changes in the length of defended coastline (excluding flood banks) over the period since 1820.

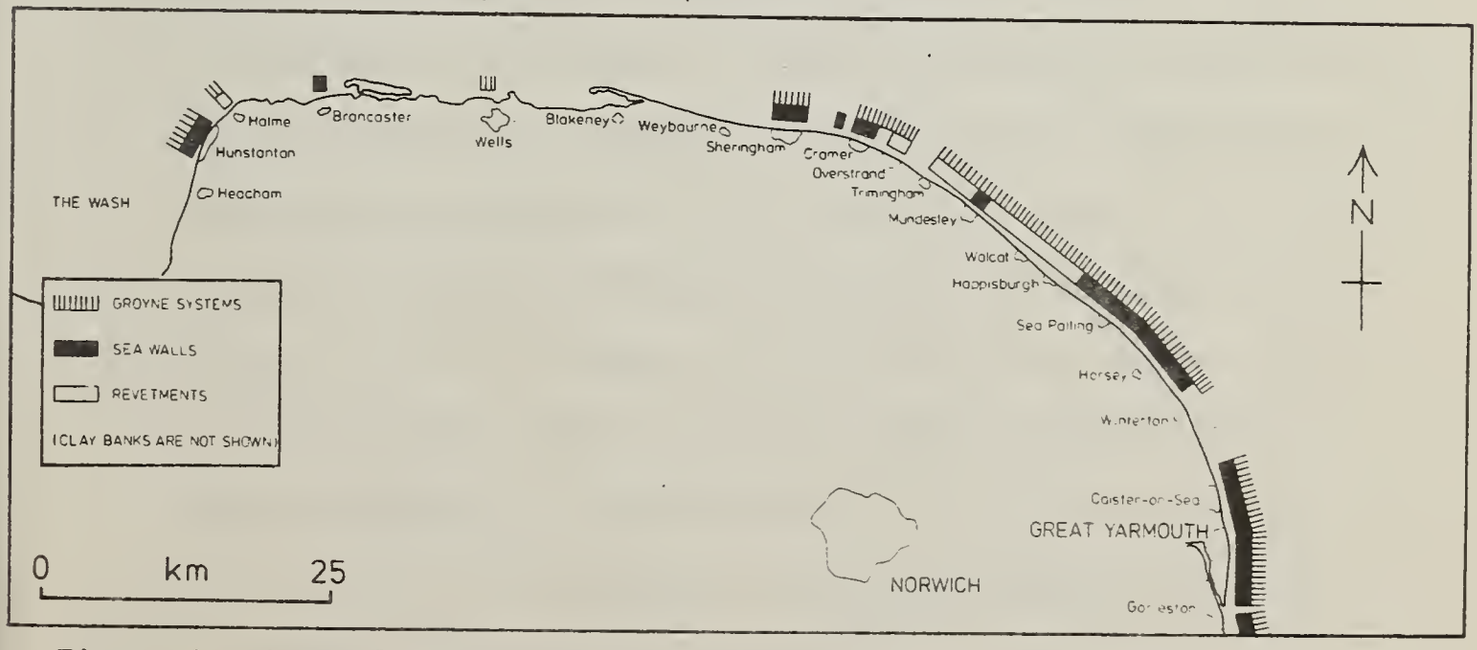

Figure 4. Coastal defences along the Norfolk coast (excluding flood banks)1975.

offshore or from the Wash subsystem. It is unlikely to be affected by any engineering developments other than a Wash barrage. The other is a measured input from the high cliffs, modified by coastal defences over the last two decades, but still near to its natural level. That input must be responsible for the sediment balance along the whole coast from Happisburgh to Great Yarmouth. If it is cut off, it is difficult to see how littoral drift levels can be maintained without beach lowering and increasing erosion all the way to the Yare mouth. Just as sediment trapped in Lake Nasser is no longer contributed to balance sediment loss from the Nile delta, disturbance of Norfolk's river of sand could be felt far from the source area at Trimingham.

As geologists or geomorphologists this must disturb us. In the long term it threatens the holiday beaches of the most heavily used section of the Norfolk coast. Despite the larger units of our local government system it still involves the classic problem of one District taking action of profound significance for the authority downdrift. The sooner our model of sediment movement is appreciated as a guide to the impact of current policies, the sooner those policies will be re-examined. It is not as if we have no alternative to pursue. We must first stress the value of the sediment contributed by the eroding cliffs, and the length of coastline benefited by it. If we had to supply that sediment to the beaches ourselves, it would cost us half a million pounds every year. Even its transport by natural processes along 20 km of open beach, despite the loss of half of it on the way, would cost something like £450,000 if we did

it by lorry. Finally, where we do require beach volumes to be increased this may be better done by beach nourishment - by adding sediment to the system - than by installing groynes and hoping for the best. The very beaches that are of value to us as natural physical environments are also of great value to holiday makers and deserve to be retained. And even geologists go on holiday sometimes!

Acknowledgement

The work I have described has been carried out under contract from the Department of the Environment through the Hydraulics Research Station. The data, and many of the ideas, have come from those supervising or employed on the project, Dr. I.N. McCave, Dr. C. Vincent, Dr. S. Craig-Smith, Dr. G. Cambers, Miss S. Aranavuchapun, S. Waddingham, A. Simmonds, K. Ratcliffe and J. Clarke. The views I express here are my own, and are in no sense the responsibility of the Department of the Environment, the Hydraulics Research Station or my colleagues on the project.

East Anglian Coastal Research Programme: Reports

1. G. Cambers & S.J. Craig-Smith. Beach profile location, December 1974.
2. S.J. Craig-Smith, A.C. Simmonds & G. Cambers. East Anglian sea defence policy, June 1975.
3. G. Cambers. Sediment transport and coastal change. July 1975.

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K.M. Clayton. Coastal defence policy on the East Anglian coast. Geographia Polonica (in press).

I.N. McCave. Mud in the North Sea. In North Sea Science, ed. Edward D. Goldberg (MIT Press) 1973, pp. 75-100.

SECRETARY'S REPORT FOR 1975

Six lecture meetings were held during 1975: January (the Presidential Address for 1974), Mr. Hywell Evans on 'Aspects of the Glacial Geology of West Norfolk'; February, Dr. C.T. Baldwin, 'Tracks and Trails: Did Trilobites Wear Wellingtons?'; March, Dr. J.R. Cann, 'Plate Tectonic Processes at Mid-Ocean Ridge Crests'; October (the Presidential Address for 1975) Professor K.M. Clayton, 'Norfolk Sandy Beaches: Applied Geomorphology and the Engineer'; November, Mr. P.J. Lawrence, 'The Lower Palaeozoic Geology of the Oslo Region'; December, the Annual General Meeting followed by three geological films and members' slides. The March lecture by Dr. Cann was held at King's Lynn County Technical College. This is the first time that the G.S.N. has arranged a lecture meeting outside Norwich. It was judged a success and it is hoped such meetings will become a regular event in future.

There were three committee meetings during the year.

Mr. Norman Peake, who has held the office of Field Meeting Secretary for several years, has resigned from that position. I would like to record the Society's appreciation for all the time and effort that Mr. Peake has given over the years, not only in organising the annual programme of field meetings but in many other ways as well. I am glad to report that he will continue to help the Society in the position of Committee Member.

Other members who left the Committee were Professor Brian Funnell, Mr. Norman Sidebottom and Mr. Alan Fowler. Professor Funnell and Mr. Sidebottom have both finished a three year term, and Mr. Fowler has moved to Edinburgh. Grateful thanks are due to them for their help.

At the A.G.M. Mr.P.J. Lawrence was elected Field Meeting Secretary and the three new Committee Members are Dr. P.N. Chroston, Mrs. E. Evans and Mr. N.B. Peake.

February 1976 Christopher J. Aslin

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The Geological Society of Norfolk exists to promote the study and knowledge of geology, particularly in East Anglia, and holds monthly meetings throughout the year.

Visitors are welcome to attend the meetings and may apply for membership of the Society. For further details write to the Secretary: Dr. C.J. Aslin, the University Library, University of East Anglia, Norwich NR4 7TJ

Copies of this Bulletin may be obtained, £1 (plus 20p postage), from the Secretary at the address given above; it is issued free to members

The illustration on the front cover is from Figure 80 (page 468) of the second edition of H.B. Woodward's "The Geology of England and Wales", published by G. Philip & Son, London in 1887. It is after a photograph of a Chalk pit at Whitlingham, near Norwich. The beds above the Chalk with flints, seen best to the right of the picture, comprise 4.5 to 6 m of Norwich Crag Series, made up from bottom to top of: Stone bed; False-bedded sand and gravel, with shells; Impersistent laminated clay, and shelly seam; and Pebbly gravel and sand, with seam of shells.

BULLETIN OF THE GEOLOGICAL SOCIETY OF NORFOLK

No. 29 1977

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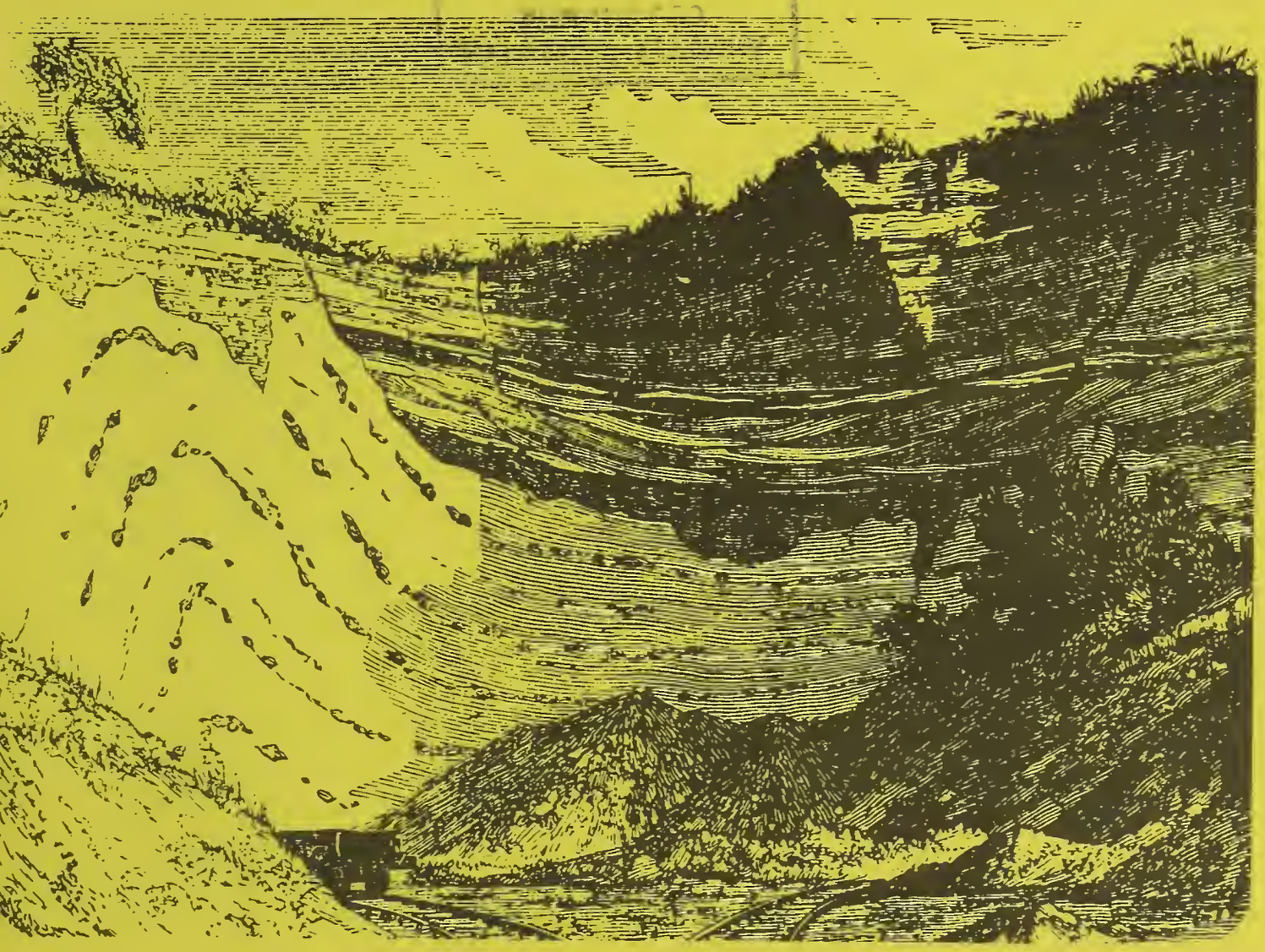

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Loess in N.E. Norfolk

Review of Marine Plio-Pleistocene

Occurrence of Colus

Sediments from Holkham Beach

Secretary's report for 1976

BULLETIN of the GEOLOGICAL SOCIETY OF NORFOLK

No. 29 October 1977
Editor: P.N. Chroston
School of Environmental Sciences, University of East Anglia,
Norwich NR4 7TJ

EDITORIAL

Richard Joby has acted as our editor for some years and the Society owes him a considerable debt of gratitude for his excellent work in the production of the Bulletin. As new editor, I trust that the Bulletin will continue to serve the Society and all others who have a special interest in the geology of Norfolk.

In the production of this issue I wish to thank Professor Brian Funnell for his help and advice, Mr. Peter Scott for photographic assistance and Mr. David Mew for artwork.

Bulletin No. 30 will be issued in Summer 1978. Contributions should be sent to me as soon as possible, and no later than December 31, 1977.

Will contributors please note that manuscripts are acceptable in legible handwriting, although typewritten copy is preferred. In either case it would be a great help if details of capitalisation, underlining, punctuation, etc., in the headings and references (particularly) could conform strictly to those used in the Bulletin. Otherwise publication may be delayed.

Illustrations intended for reproduction without redrawing should be executed in thin, dense, black ink line. Thick lines, close stipple, or patches of black are not acceptable, as these tend to spread in the printing process employed. Original illustrations should, before

reproduction, fit into an area of 225 mm by 175 mm; full use should be made of the second (horizontal) dimension, which corresponds to the width of print on the page, but the first (vertical) dimension is an upper limit only. All measurements in metric units, please.

P.N.C.

Bull Geol. Soc.Norfolk, 29, 3-22 (April 1977)

DISTRIBUTION OF LOESS IN NORTH EAST NORFOLK

W.M. CORBETT*

Abstract

The distribution of a surface thin silty drift is plotted in north-east Norfolk between Norwich and the coast. To the south-west there is less than 20 per cent silt and to the north-east more than 30. Local variation in thickness in relation to ground surface relief is shown for a block of 480 borings on a 25 m grid at Hole Farm, Plumstead near Holt. The pattern, thick drift in valleys and re-entrants, thin striations on crests and none on steeper slopes has been strongly influenced if not caused by local movement.

Introduction

Soil mapping of O.S. sheets TG13 and 14 in 1968 and 1969 found a thin surface drift with more silt on all sites but the steepest slopes and the highest most exposed crests (Corbett and Hodge 1976). On flat uplands this drift is 40 to 70 cm thick and in valley floors and other concave sites up to 200 cm. In soil profiles a sharp textural change separates it from the underlying material. On the Cromer Ridge this material consists of gravels with less than 10 per cent silt, and in the lowlands to the south and east it is represented by the North Sea Drift (Norwich Brickearth), a loamy till with more clay and 20 to 30 per cent silt (Fig. 1, from Corbett and Tatler 1974).

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Catt et al. (1971) studied its particle size distribution and mineralogy at five sites in north-east Norfolk. The particle size distribution was bi-modal with the main peak at 40 μm and a more or less pronounced secondary peak at 250 μm. The silt fraction was mineralogically similar to that of the Hunstanton till in north-west Norfolk and to the loess at Pegwell Bay in Kent and they suggested it was mainly wind blown derived by deflation of the Weichselian glacial outwash. It was pointed out that this drift had material, sand, clay and stones, foreign to loess and lacked some other characteristic features. They referred to it as "Cover Loam".

Perrin et al. (1974) plotted zones in south-east England with surface drift enriched by sand, silt and/or sand and silt; north-east Norfolk, within zone IV, having sand and silt. Both the sand with a mean particle size at 236 μm and a SE of 55 and the silt with a mean of 36.2 μm and a SE of 0.75 were considered aeolian, the sand being deposited before or during the last intense periglaciation in the Devensian and the silt later. They suggested that the present sandy silt topsoil was derived by biological mixing and that the silt in Zone I, England south of the Thames, had a geographic association with the loess in north east France.

Veenstra et al. 1971 studied cover sand distribution in Holland and Belgium on the basis of grain size and shape, found that grains above 400 μm are rare, only finer material being suited to wind transportation.

North-east Norfolk is an area of intense arable farming and a major limitation to crop growth is lack of moisture in the growing season. There is a mean deficit between rainfall and transpiration of about

150 mm (6 inches). The capacity of the soil to store moisture to offset this deficit is related to particle size, in particular the content of silt and fine sand. Deep silts are the only upland soils which avoid drought stress and sandy soils without a silty surface are commonly grass, heath or forest. For irrigation the soil storage capacity controls frequency and amount.

This is a background study in the production of a soil map of the County. Its aim is to plot the distribution of the silty surface drift, "Cover Loam", at the regional and local scales.

General Distribution

Method. Samples from a depth of 35 cm were collected at the 114 sites in east Norfolk and north-east Suffolk shown in Fig. 2. To avoid contamination by local movement all were located on flat crests. 39 of these sites were in three transects running parallel 2.8 km apart, from Mattishall near East Dereham, north-east to the coast at Mundesley. The transects, 37 km long were divided into 13 equal sections of 2.8 km and a flat crest site sampled in each section. At each site 9 samples were taken in a cross shaped pattern with an interval between samples of 10 m. The transects were aligned at right angles to the boundary given by Catt *et al*. (1971) and crossed it about one-third of the way along their length. 55 additional sites were sampled, one in each quadrant of every 2½" map to the north and east of Catt's boundary including as well the sheets which lie immediately to the south and west. At each site three samples were taken at the points of an equilateral triangle with a 10 m side. The remaining 20 sites are those soil profile pits on flat crests sampled in the detailed soil surveys

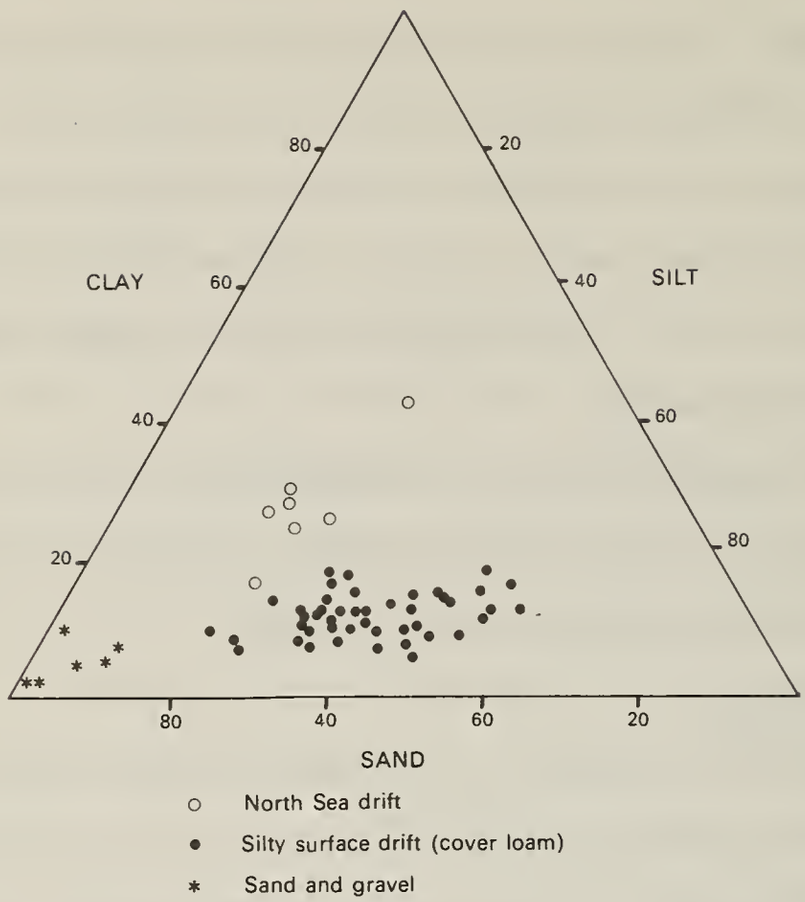


Fig.1 Size class fractions of drifts in north-east Norfolk.

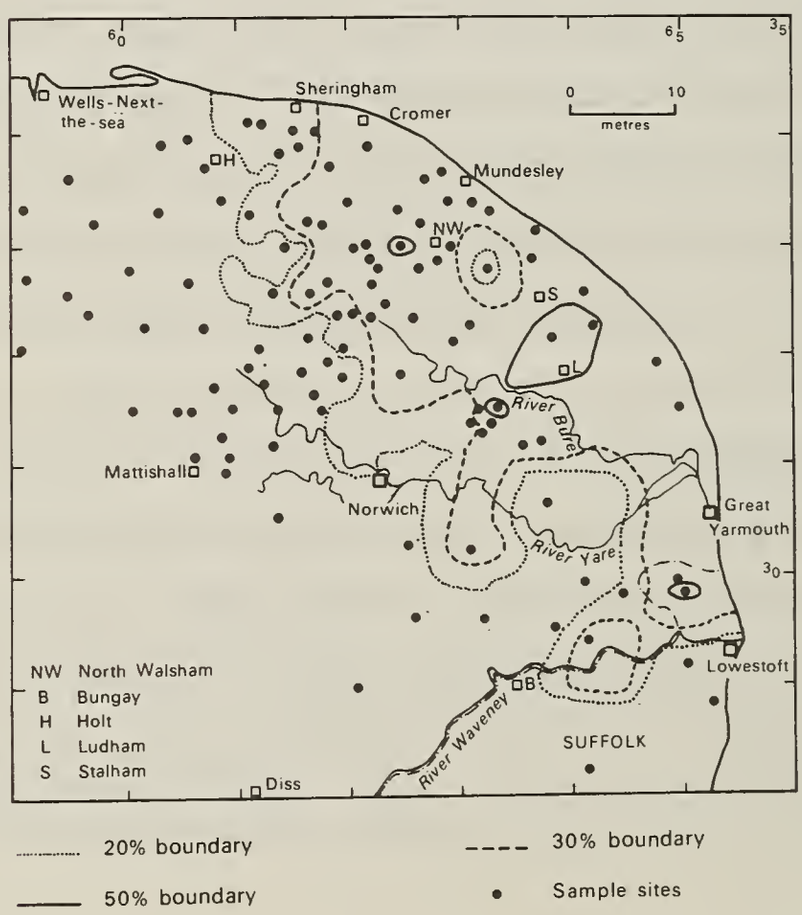


Fig.2 Subsurface silt in north-east Norfolk.

of 2½ inch sheets TM49, TM28, TG11, and TG13/14.

Particle size distribution in the fine earth (less than 2 mm) was determined on one or more samples from each site, using the pipette method after pretreatment with hydrogen peroxide to remove organic matter and dispersion overnight with Calgon (sodium hexametaphosphate). The fractions for all samples excluding the soil profile pits were, < 10 μm, 10-53 μm, 53-105 μm, 105-250 μm, 250-500 μm, 500 μm-1 mm, and 1 - 2 mm. The silt fraction in samples from soil profile pits is 2 - 50 μm.

Results. Fig. 2 is based on the printout of a SYMAP program for the 114 sample points. It shows a zone 5 to 15 miles wide running along the coast from Sheringham to Lowestoft with 30 to 50 per cent silt in the subsurface horizon of upland soils. Within this zone immedi ately to the south of Stalham and centred about Ludham is an extensive patch with 50 to 60 per cent subsurface silt and in three other localities there are small patches with this amount. To the south-east of a line from Holt to Norwich and Bungay subsurface silt is less than 20 per cent and within the 30 per cent zone there is a small patch between North Walsham and Stalham with this amount.

Transect data given in Table 1 and in Figs 3 also show the clear break between a north-east section with silt values above 30 per cent and a south-west section with values below 20. Within the silt zone eight samples at site A3 had a mean value of 41.5 ± 14.2 per cent and 9 samples at site A6 outside the silt zone a mean of 13.0 ± 2.0 per cent. The mean value for all transect sites within the silty area is 39.7 ± 7.5 per cent and sites outside 13.6 ± 3.6 per cent.

Table 1 Coarser sand (500μm-2mm), finer sand (105-500μm) along transects from Mattishall to Mundesley

S.W. N.E.

		9	8	7	6	5	4	3	2	1	0_1	0_2	0_3	0_4	Mean 0_4–3	Mean 5–9
A	500um – 2mm	6.2	4.2	4.0	6.2	3.8	4.5	4.6	5.6	2.3	4.8	10.6	5.9	10.5	6.3 ± 3.1	4.8 ± 5.2
	105–500um	54.7	44.0	39.6	57.5	58.2	43.6	26.1	28.8	14.1	38.4	33.0	28.3	29.9	28.4 ± 7.5	50.8 ± 8.5
	10–53um	19.7	16.2	13.3	13.2	14.6	22.1	41.5	37.7	45.3	38.9	36.9	37.8	33.2	38.9 ± 3.8	15.2 ± 2.9
B	500um–2mm	4.9	5.3	6.7	6.2	17.3	14.5	5.2	8.2	6.9	5.0	6.4	5.0	5.7	5.6 ± 1.0	8.6 ± 5.1
	105–500um	52.4	45.2	58.7	53.1	56.4	51.1	64.6	41.8	22.6	18.4	29.9	38.4	16.0	25.1 ± 9.1	54.5 ±
	10–53um	12.7	16.7	14.4	15.3	7.3	16.3	17.2	24.2	40.6	53.9	41.6	30.2	47.5	43.0 ± 8.9	12.5 ± 5.7
C	500um–2mm	4.1	3.6	5.5	53.3	2.9	7.0	6.1	5.0	5.6	9.1	4.5	15.6	11.3	8.5 ± 4.4	
	105–500um	42.1	39.1	61.4	32.0	69.9	66.6	39.2	41.0	16.9	32.7	21.6	48.0	28.0	31.7 ± 11.7	51.9 ± 16.0
	10–53um	13.1	12.7	14.5	3.9	11.9	14.1	25.0	32.1	44.4	44.0	48.0	22.1	33.6	37.3 ± 9.7	11.8 ± 3.9

Means A+B+C	500um–2mm	6.3 ± 3.8	(Loess area)	6.9 ± 3.3	(outside)
	105um –500um	28.5 ± 9.3	(Loess area)	52.6 ± 10.4	(outside)
	10um–50um	39.7 ± 7.5	(Loess area)	13.6 ± 3.6	(outside)

The boundary is clearly expressed in Fig. 4 using the data from all 114 sites. Subsurface silt values rise from about 15 per cent to about 35 per cent across a relatively narrow boundary. In the transect data one site in each transect A4 (TG 142, 234) near Cawston, B2 (TG 198, 252) near Marsham and C3 (TG 191, 202) near Hevingham have values between 20 and 30 per cent. Fig. 2 shows that the transition zone is one to four miles wide. The direction of the boundary to the north of Norwich follows Catt's fairly closely but to the south it has additional lobes towards Loddon and Beccles.

Fig. 3 also shows along the transect the associated change in fine sand. The correlation coefficient for percentage silt against sand fractions movable by wind, 105-500 μm, gives 66.5 per cent of the variance accounted for. The correlation coefficient for coarser sand, too heavy for saltation, 500 μm - 2 mm, gives only 8 per cent of the variance accounted for.

The mean percentage of the finer sand for all sites within the silt area is 28.5 ± 9.5 per cent and outside the silt area 52.6 ± 10.4. The values for coarser sand are 6.3 ± 3.8 and 6.9 ± 3.3 per cent respectively. Across the silt boundary there is a clear decrease in the finer sand but little change in the coarser sand percentage.

The low percentage coarser sand suggests that the surface drift in both silty and sandy zones is almost purely aeolian. Soil profile pits on crests throughout the silt zone show that the depth of the aeolian surface drift ranges between 40 and 70 cm and its survival shows that biological mixing has been within this relatively thin layer. Three stage soil profiles of the same depth range with silty surface

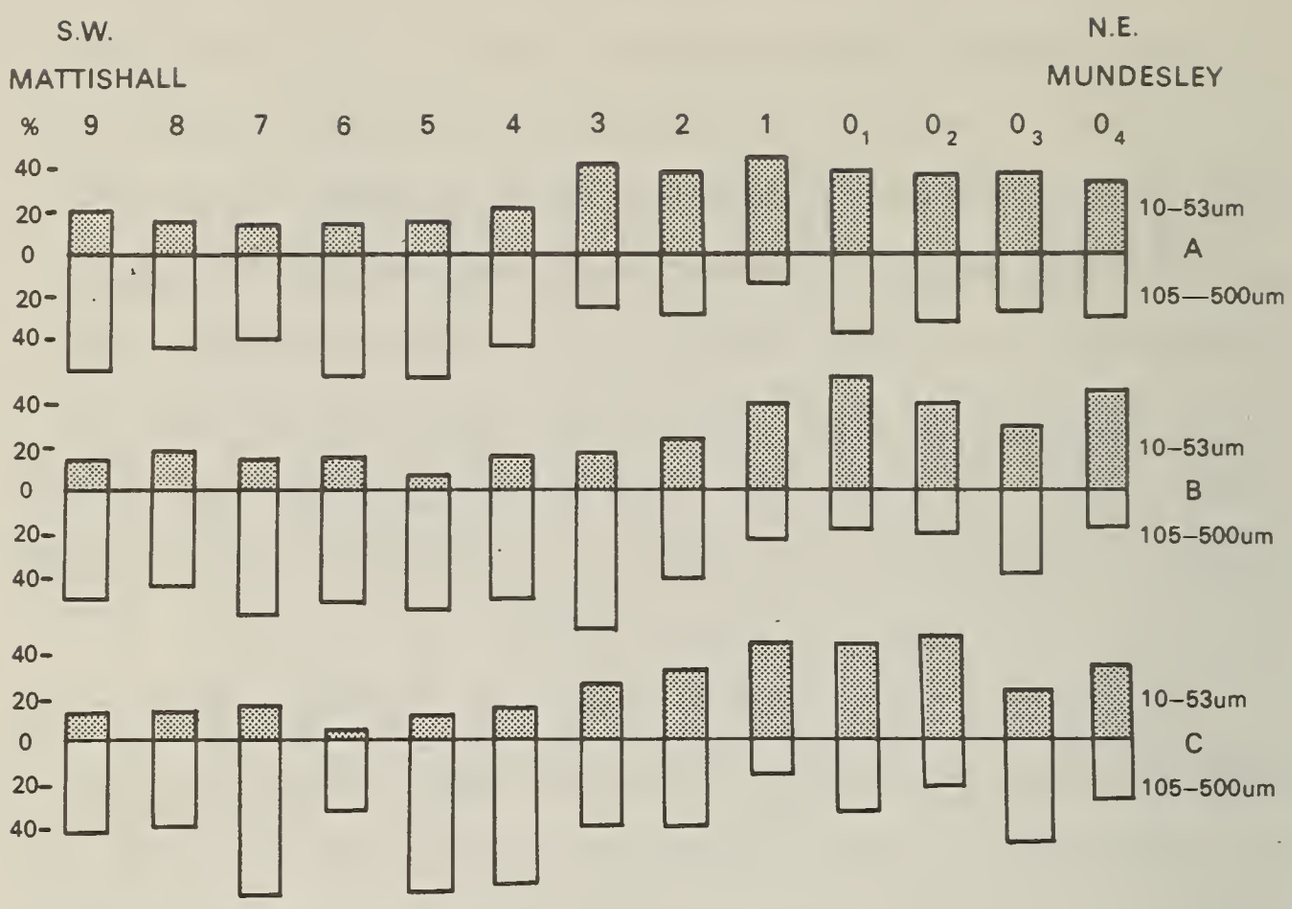


Fig.3 Subsurface silt and sand along transects from Mattishall to Mundesley

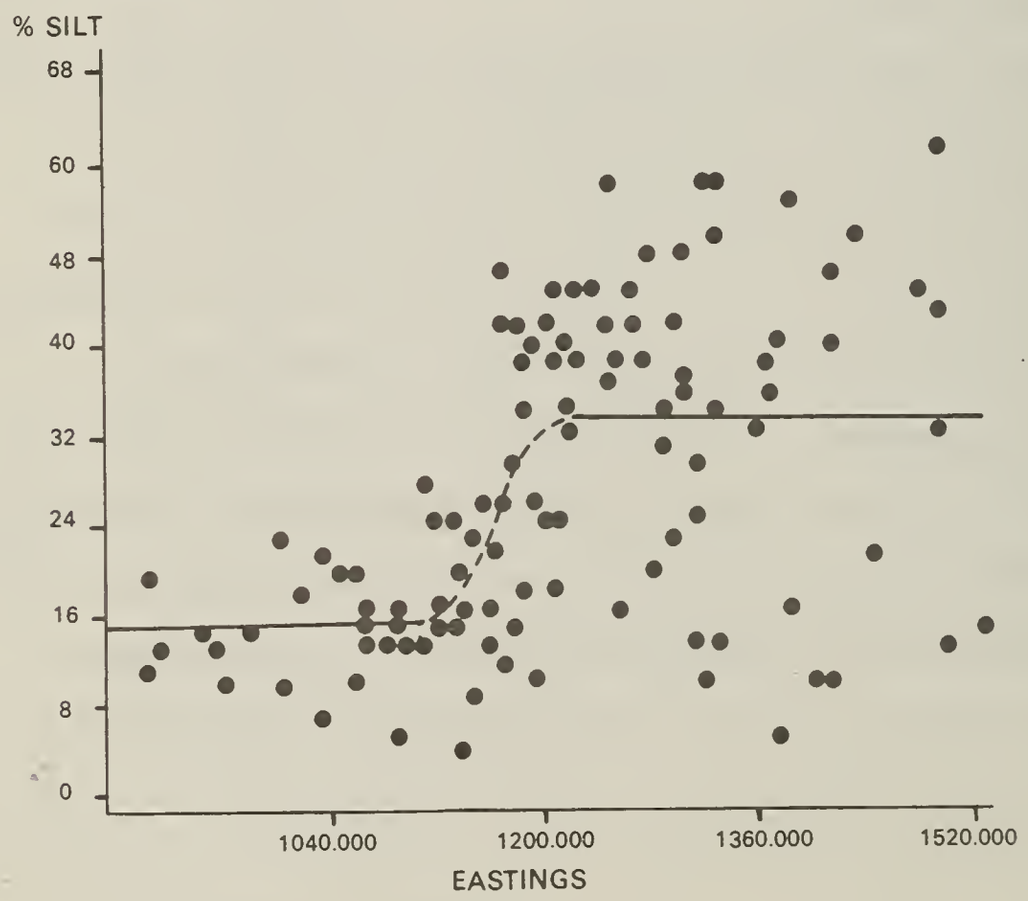


Fig.4 Log curve percentage subsurface silt/eastings.

horizons unimodal in the 2 - 50 μm range, and sandy subsurface horizons unimodal in the 200 - 500 μm range over a clayey till are common on OS sheet TG31. Similar stratigraphic evidence at Great Blakenham, Suffolk (TM 103503), is used by Perrin to post-date the silts and the absence of cryoturbation features on silty sites to put the sand deposition in or before the last intense periglaciation period in the Devensian and the silts later.

Local Distribution

Method. Soil mapping of OS sheet TG 13/14 showed that the thickness of silty surface drift varied with position in the landscape. The pattern is expressed most fully on the southern boundary of the Cromer Ridge where with a pronounced local relief of about 21 metres (70 ft), the landscape has four facets, slopes of 5° to 15° on southern and western aspects, flat crests with shallow re-entrants, narrow concave valley floors and gentle 1° to 3° slopes to the east and north. Silty surface drift is thick on valley floors, absent from steep slopes and thin on crests and gentle slopes.

Aerial photographs of the fields around Hole Farm, Plumstead, TG 114357, Plate 1, in 1970 and 1971 showed prominent growth patterns in sugar beet and barley. The dark tones of better growth reflected increase in available soil water on silty as opposed to stony and sandy soils. The pattern appeared to delineate extremely precisely the variation in depth of surface silts and showed that the understanding of distribution from soil mapping was crude and generalised. A network of thicker silty drift branched from dry valleys to re-entrants and from there in thin trails up onto crests. The crests have also

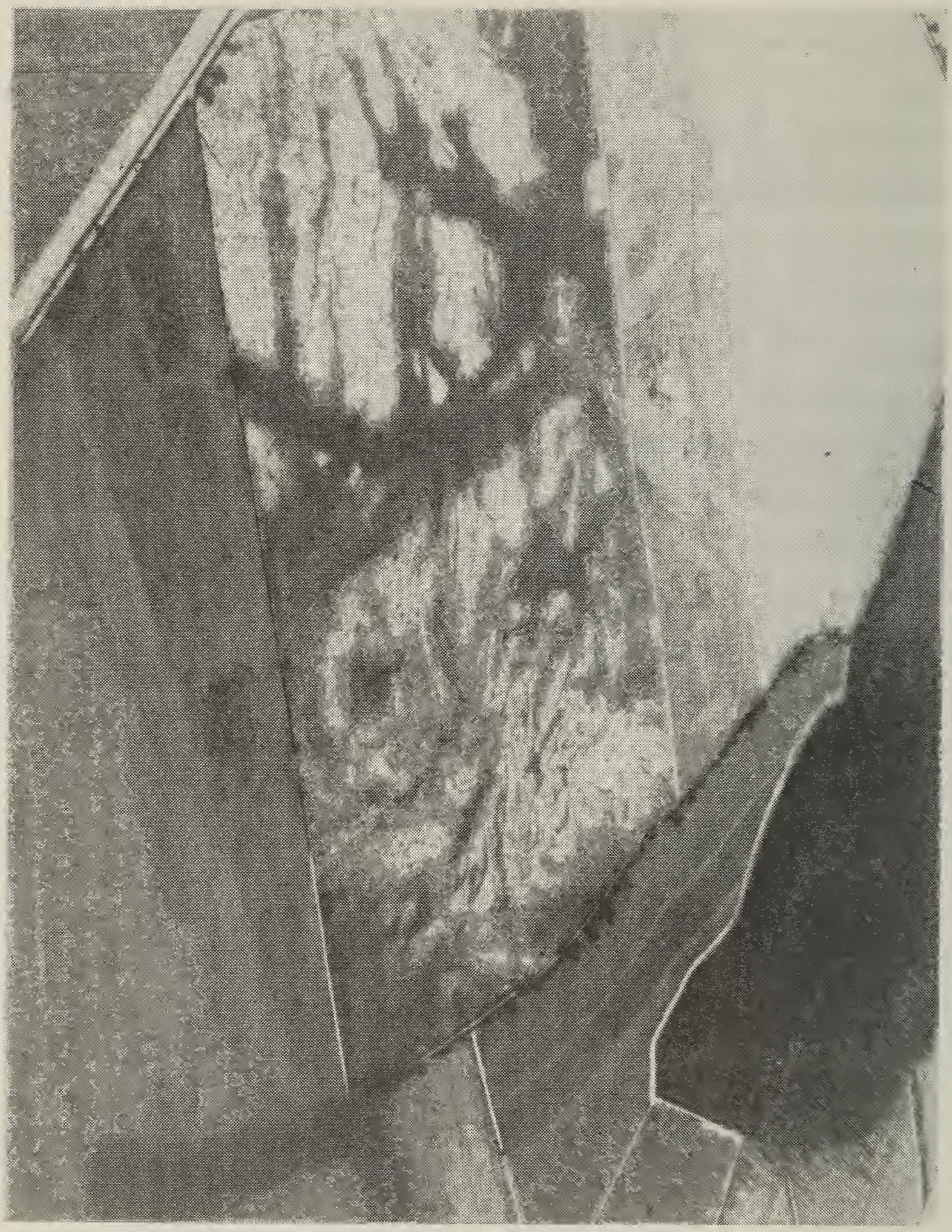


Plate 1 Sugar beet at Hole Farm, Plumstead, August 1970.

narrow irregularly distributed striations, a few metres wide, unconnected with the heads of re-entrants.

This field was sampled in three ways.

1. A block of 480 sites on a regular 25 m grid was pegged out to cover the eastern half of the field in Plate 1. This block covered all facets of the landscape. At each site the thickness of silty surface drift, the depth to the textural discontinuity at the underlying gravel surface was measured by hand auger and the site altitude by theodolite.

2. A block of 93 sites on a regular 20 m grid was pegged on the crest in the north west corner of the same field. The thickness of silty surface drift was again measured by hand auger. This site was part of an area contoured at 1/3 m photogrammetrically as an exercise by the Geography Department of the University of Glasgow. This was used as a base map.

3. Four transects were located on aerial photographs to cross thicker silty drift, at the highest altitude a narrow trail on the crest; below the same trail as it connected with the head of the re-entrant, below again in the re-entrant and finally in the dry valley. The sampling interval along these transects was 10 m and at each site the thickness of silty drift and the presence or absence of stones was measured by augering. Site altitude was taken from the 1/3 m contour maps.

One site, site 10 on transect 3 Fig. 7, on the floor of the re-entrant had silty drift more than a metre thick. A soil profile pit, 2 m deep to the underlying gravel was sampled and analysed for particle size distribution by the pipette method.

Results. Fig. 5, the variation in the thickness of silty drift in relation to local relief on the east side of the Hole Farm field was

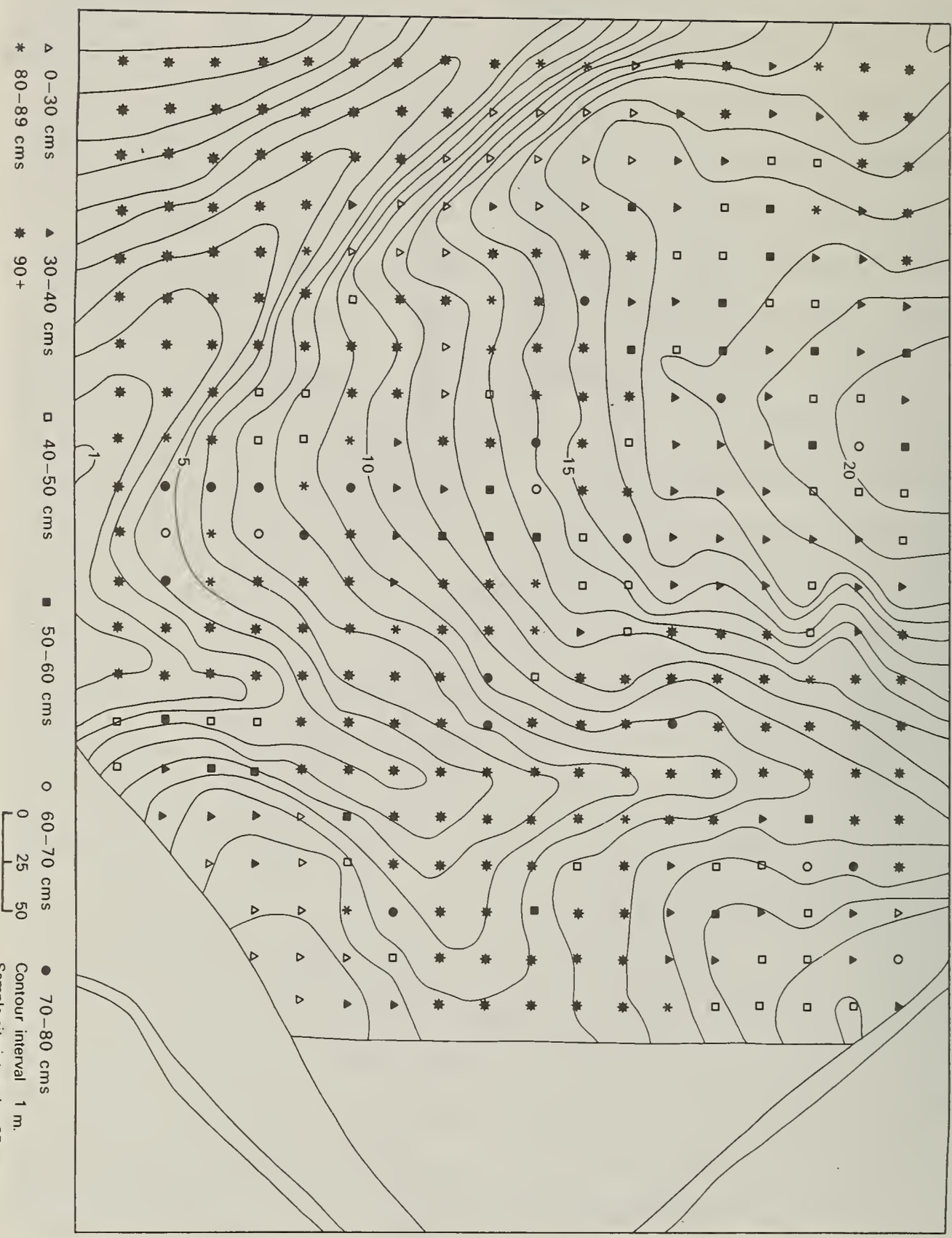
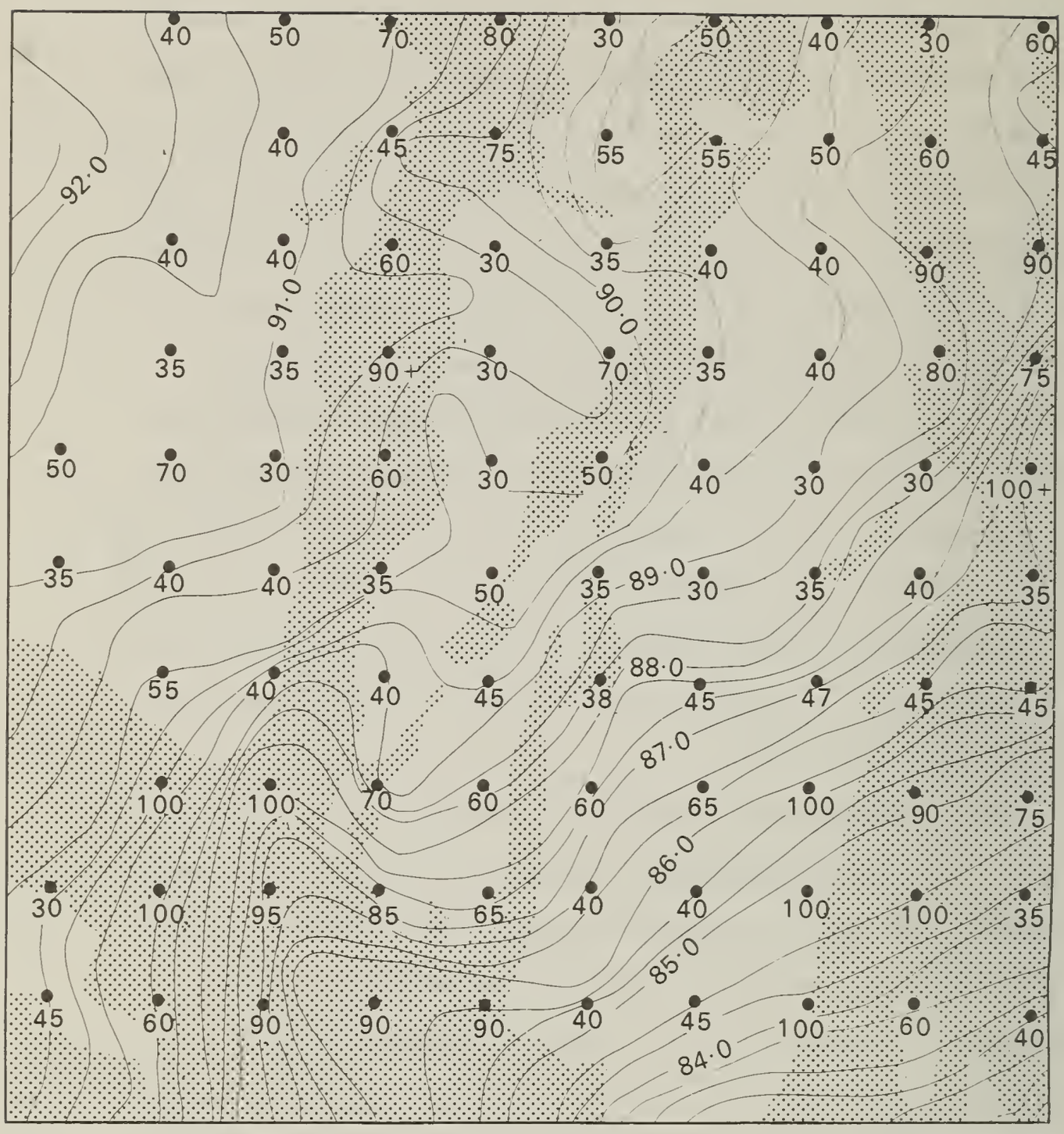


Fig.5 Thickness of silty drift in relation to relief at Hole Farm, Plumstead,TG 117 345.

made by superimposing 10 m interval ground surface relief contours on the pattern of silty drift thickness produced by a SYMAP program on the 480 sample points. The pattern is broadly similar to that found in soil mapping but the relationship to relief is less exact. Thick deposits extend from valley floors up onto quite steep lower slopes and from the head of re-entrants in thin trails up onto crests. Silty drift is absent from the steepest slopes and the narrower crests. On crests, at least in the landscape sampled, there is no extensive area with a uniform intermediate thickness of silty drift. These observations fit the crop growth patterns on aerial photographs. Using the 480 site data regression of thickness against altitude gives only a percentage variance accounted for of 25.9 and against altitude and slope of 28.7. The sampling grid appears too coarse particularly for the pattern on crests.

Fig. 6 shows the local variation in thickness of silty drift on a crest in the north-west corner of the same field using a 20 m sampling interval. The sampling sites are marked by their thickness of silty drift and the crop pattern has been transferred from an aerial photograph. The mean depth of the good crop growth strata is 70 ± 23 cm and of the poor growth strata 46 ± 16 cm. Both strata have a marked asymmetric distribution of thickness classes and the nature of this asymmetry differs. Using the non-parametric Mann-Whitney U test the difference in the range of thickness is sufficient at the 0.001 level. On aerial photographs the dark tones of better crop growth do occur on the thicker silty drift and can be used to plot its distribution.



0 20 40
metres

Grid interval 20m.

Better crop growth

Contour interval ⅓ m

Fig.6 Thickness of silty drift in relation to crop growth, Hole Farm, Plumstead, TG 112 236.

The origin of these thin trails of silty drift on crests is unexplained. Comparison of aerial photographs with 1/3 m contour maps shows some of them to be across flats and along slopes. Some also are isolated from the heads of re-entrants and some of those which are connected to re-entrants have wider apparently deeper sections away from the re-entrant head. The surface of the underlying gravels on crests is more uneven than the present ground surface and the trails could be regarded as an infilling with loess but the relief of the underlying gravel surface thus revealed in crop growth pattern is not a drainage network.

Four sections across trails of thick silty drift from crests to dry valley floor are in Fig. 7. The thickness on crests is 50 to 100 cm, in re-entrants about 2 m and on dry valley floors about 1 m. Stone-free drift occurs only at depth on the re-entrant floor and on the gentle north and east facing slopes of the dry valleys. Some small lenses of stone-free material are on steeper slopes above ledges or breaks in the underlying gravel surface. The silty drift in all other positions in the landscape contains stones incorporated from below during mixing or movement. The great bulk of the silty drift trails which in concave sites cross the landscape are trails of movement. In the centre of the valley floor there is a prominent gravel filled channel.

The particle size distribution in the 2 m pit profile in the re-entrant floor is shown in Figs 8A and B. The silty drift is about 190 cm thick and has three zones: 0-85 cm, 85-115 cm and 115-190 cm. The silt fraction in Zone 1 increases with depth from 55 to 68 per cent,

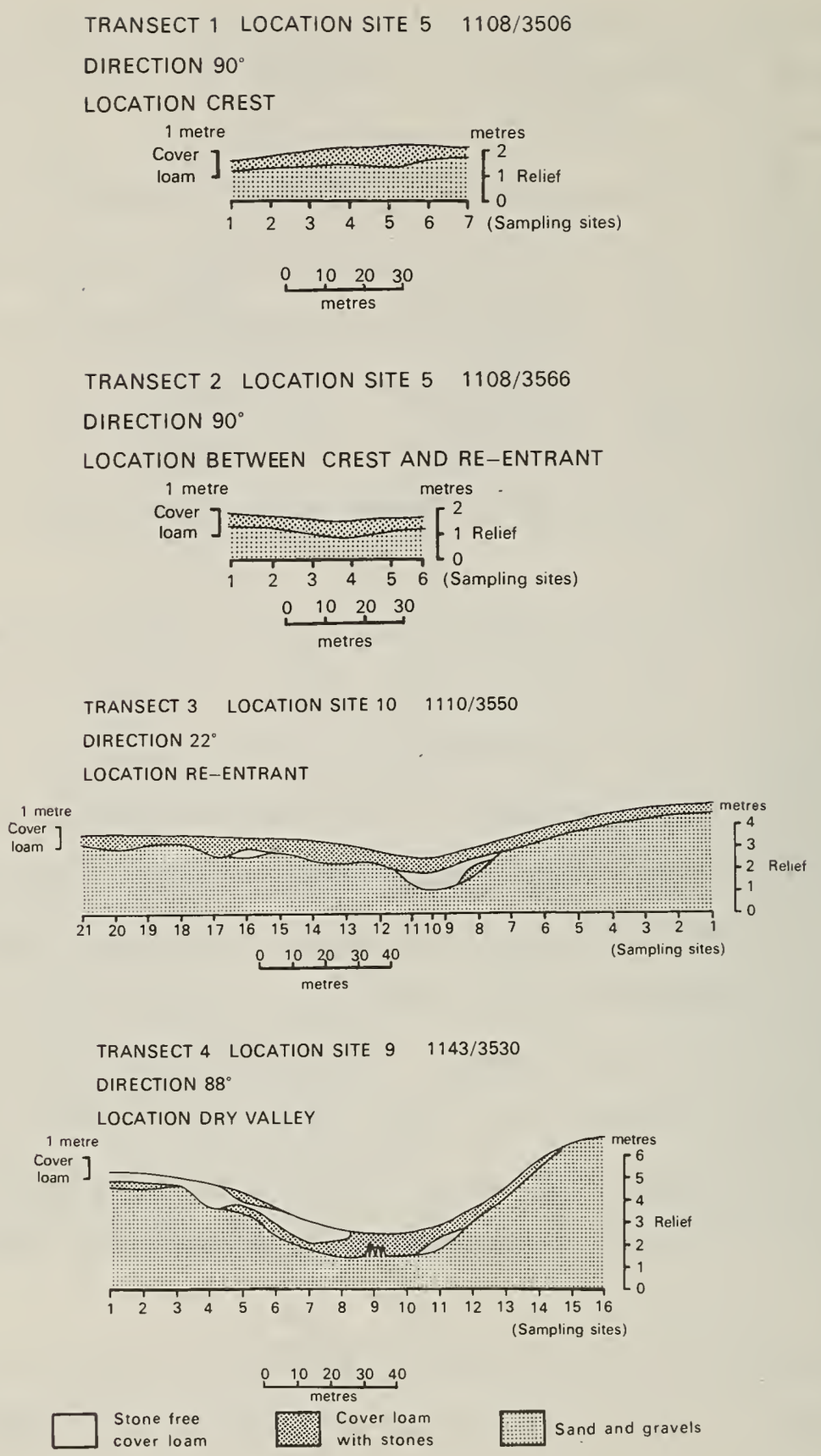


Fig.7 Relief sections across trails of silty drift at Hole Farm, Plumstead,

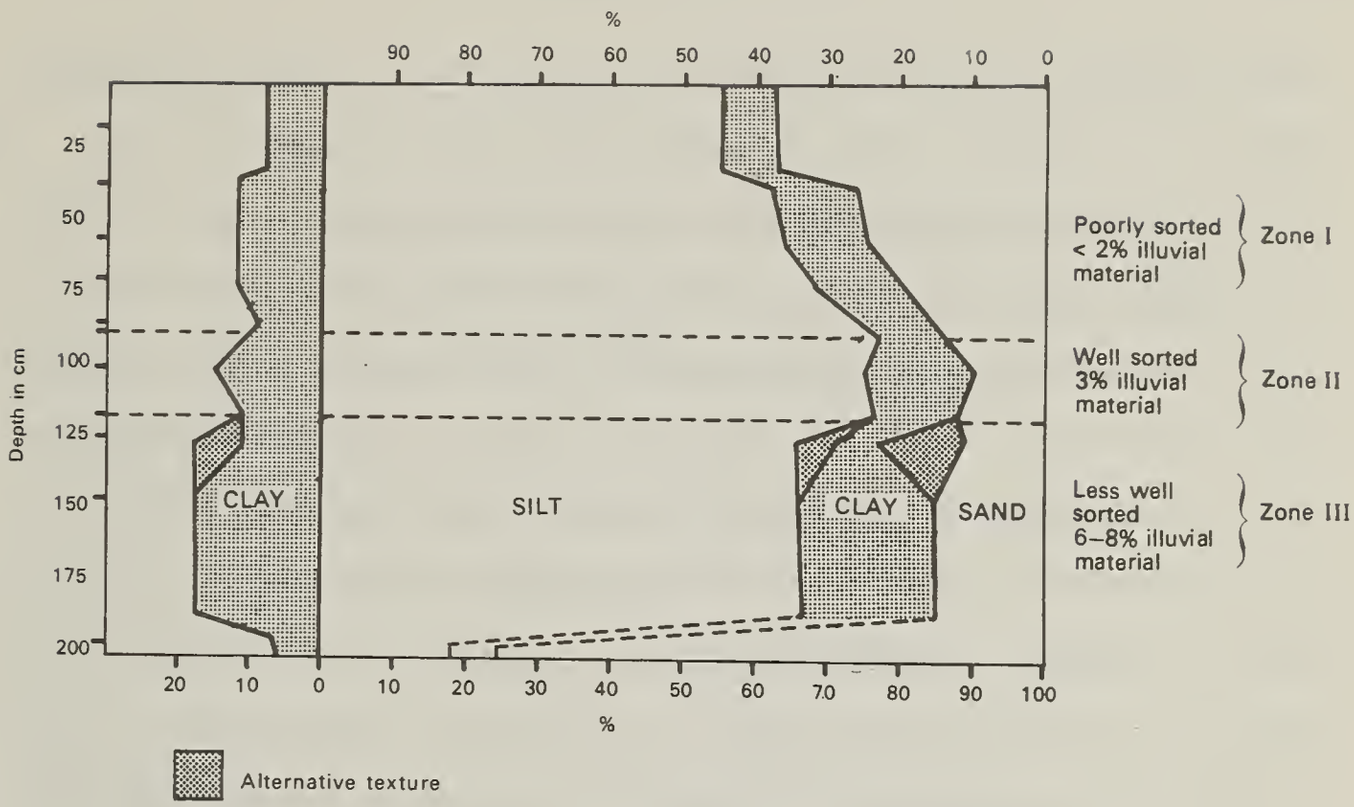


Fig.8(a)Particle size distribution in soil profile on re-entrant floor at Hole Farm, Plumstead, TG 111 355.

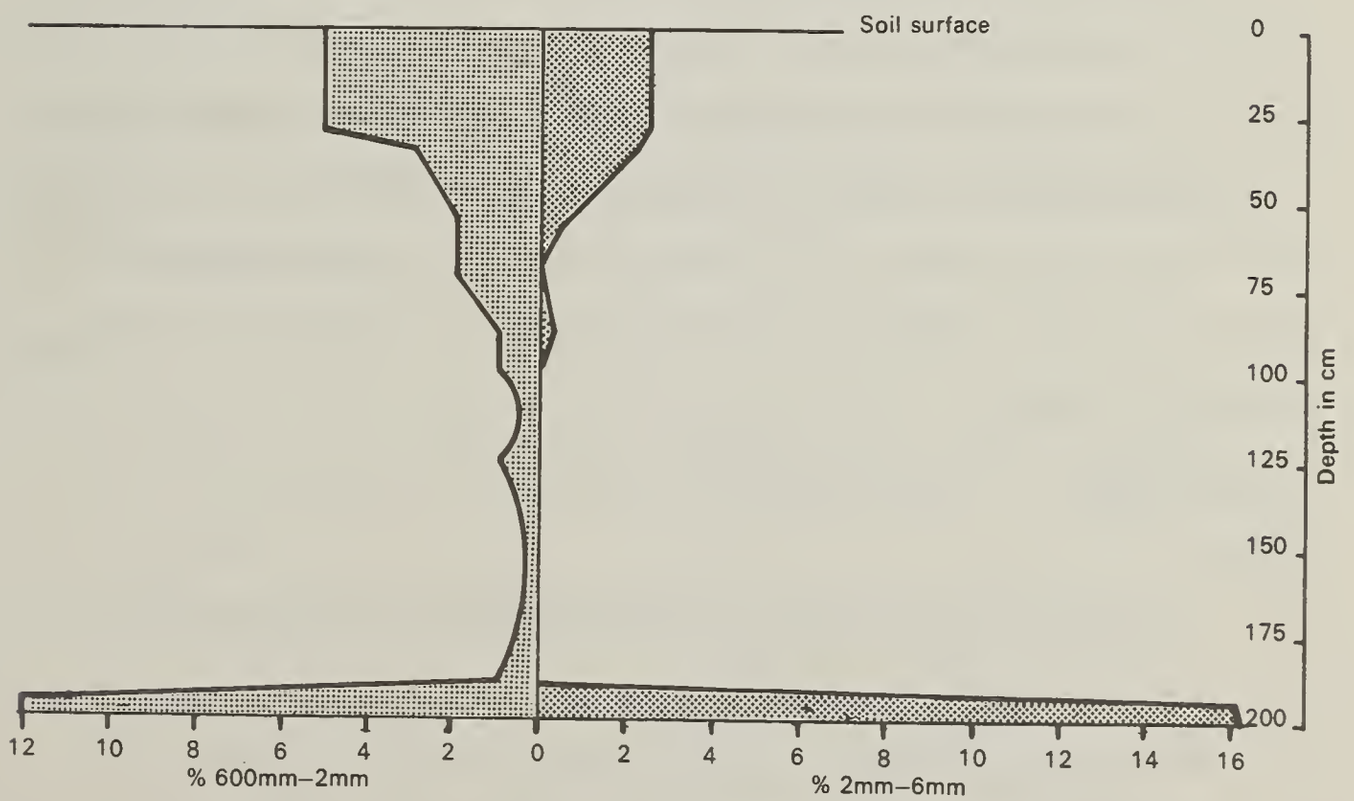


Fig. 8(b) Distribution of coarse sand and stones.

sand decreases from 37 to 20 per cent and coarse sand, above 500 μm, from 5 to 2 per cent. Clay is about 12 per cent and there are some stones. Zone 2 has more silt, less sand, variable clay, 1 per cent or less coarse sand and no stones. Zone 3 has less silt but more clay. Thin section micro-morphology shows Zone 1 to be poorly sorted with less than 2 per cent illuvial clay and silt, Zone 2 well sorted with 3 per cent illuvial material and Zone 3 less well sorted but with 6 to 8 per cent illuvial material. The colour pattern in Zone 3 is of special interest. The general colour is reddish brown 5 YR 4/4 but this is broken by paler bands 10 - 75 mm wide, light brown 7.5 YR 6/4 set vertically or obliquely. The general impression is that of peds separated by fissures of a paler contrasting colour. The paler strips have more sand. This is taken to be a fossil soil horizon.

The profile is regarded as having a two or three stage history. If Zone 3 represents a fossil soil horizon, Zone 2 is either its surface soil horizons or a separate aggradation of loess laid down on a truncated profile. Zone 1 represents local accumulation, solifluction and erosion, the latter still continuing and the product becoming increasingly more sandy as cultivation upslope cuts deeper into the underlying gravels.

Conclusions

General

1. A zone can be delineated in north east Norfolk with more than 30 per cent silt in the subsoil.
2. To the west and south is an area with less than 20 per cent silt.
3. Across the boundary there is little change in the nonaeolian fraction,

above 500 μm.

Local

4. There is a crude association of silty drift thickness with relief, thick in concave sites, thin in convex and absent from steep slopes.
5. On gravel the thickness pattern is revealed strikingly by crop growth in dry years.
6. On crests the pattern is narrow striations only some of which connect to the head of re-entrants.
7. Stone-free material is at depth in re-entrant floors and on gentle north and east facing slopes.
8. The pattern of thicker silty drift shown by crop growth is almost entirely mixed and/or transported material.

Acknowledgements

C.L. Bascomb, Soil Survey of England and Wales, provided or supervised the mechanical analysis. Eric Shepperd, Janice Brereton and Clare Ridding, student vacation workers, assisted with field work and likewise Dr. Stephen Nortcliff, King's College, London who also provided the Hole Farm regressions.

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WHATEVER HAPPENED TO THE BOYTONIAN? A REVIEW OF THE MARINE PLIO-PLEISTOCENE OF THE SOUTHERN NORTH SEA BASIN

P.G. Cambridge*

Introduction

Considerable confusion exists at the present moment due to attempts to correlate a pollen dating system, based on borehole samples from deeper water deposits, with shallow water outcrops whose stratigraphy has been based on the molluscan fauna. The small samples and the difference in facies in the borehole material does not allow for direct comparison by means of the molluscs while the lithology and state of weathering of the outcrops results in poor pollen samples. As a result the palynological correlations in the published literature have been tentative and stated with reservations. Despite this the pollen assemblage stage names have already been used on slender evidence by other workers.

Some of the present confusion is probably due to an insufficient understanding of the mass of literature on the Plio-Pleistocene and Quaternary, and to the fact that the work of early palaeontologists has never been updated in this country. As a result, most approaches are still based directly, or indirectly, on the writings of F.W. Harmer etc. This article is an attempt to update the 'classic' stratigraphic approach of these writers and thus provide a better comparison with any other system.

No serious attempt has been made to differentiate between stages, formations etc., but students of the Crags will have no difficulty in

recognising and understanding the terms used here. Attempts to form rigid systems on the Continent have ended in a proliferation of stratigraphic tables with little agreement. At present there is probably insufficient basic information but it is hoped that a generally accepted stratigraphical table of units will eventually be prepared for the whole area and that the probable temperature fluctuations will be quantified more closely than the present inferences of "cold" and "temperate" periods. These tend to be uninformative since both Britain and Canada have a "temperate" climate at present and there are considerable obvious differences in their actual temperature limits.

The review which follows is based almost wholly on the marine macro-fossils, of which the commonest are the molluscs. In this respect it has the disadvantage of being a largely monophyllatic approach, and the advantage that the divisions can be easily recognised in the field.

In East Anglia the shelly, marine sands of this period are referred to as "Crags", which is said to be a local dialect word for shelly sands. A possible derivation is the word "Craig", which in both Gaelic and Welsh means a rock. The term Crag is well known in Suffolk and is often included in place names, such as Crag Farm. An outline of the Neogene and Hologene stratigraphy of the Southern North Sea, based on the following discussion, is shown in Table 1.

The East Anglian Crag

The East Anglian Crag may be divided into four series each of which is dealt with in turn. The lithologies are summarized in Fig. 1.

Coralline Crag (Gedgravian)

The Coralline Crag has a limited exposure in Suffolk, the main mass of which is an elongate ridge in the Gedgrave-Aldeburgh area, with small outliers near Sutton, Ramsholt and Tattingstone. An origin as a series

			ANTWERP, BELGIUM		GREAT BRITAIN	
CAENOZOIC	HOLOGENE	HOLOCENE			WEYBOURNIAN	WEYBOURNE CRAG OF CROMER SERIES
		PLEISTOCENE	(TIGLIAN OF NETHERLANDS)		NORVICAN	NORWICH CRAG SERIES Scrobicularia CRAG
	NEOGENE	PLIOCENE			ORWELLIAN {BUTLEYAN, NEWBOURNIAN}	UPPER RED CRAG
			MERKSEMIAN	SANDS OF MERKSEM	WALTONIAN	LOWER RED CRAG
			SCALDESIAN	SANDS OF KRUISSCHANS SANDS OF KALLO	HIATUS	ST. ERTH CLAYS
				SANDS OF LUCHTBAL	GEDGRAVIAN	CORALLINE CRAG
			KATTENDIJKIAN	SANDS OF KATTENDIJK	HIATUS	
		MIOCENE	DEURNIAN	SANDS OF DEURNE	HIATUS	BOXSTONES ↑↓ LENHAM BEDS ↑↓
			ANVERSIAN	SANDS OF ANTWERP		(EXACT POSITION UNCERTAIN)

Table 1. The Neogene and Hologene Stratigraphy of the Southern North Sea.

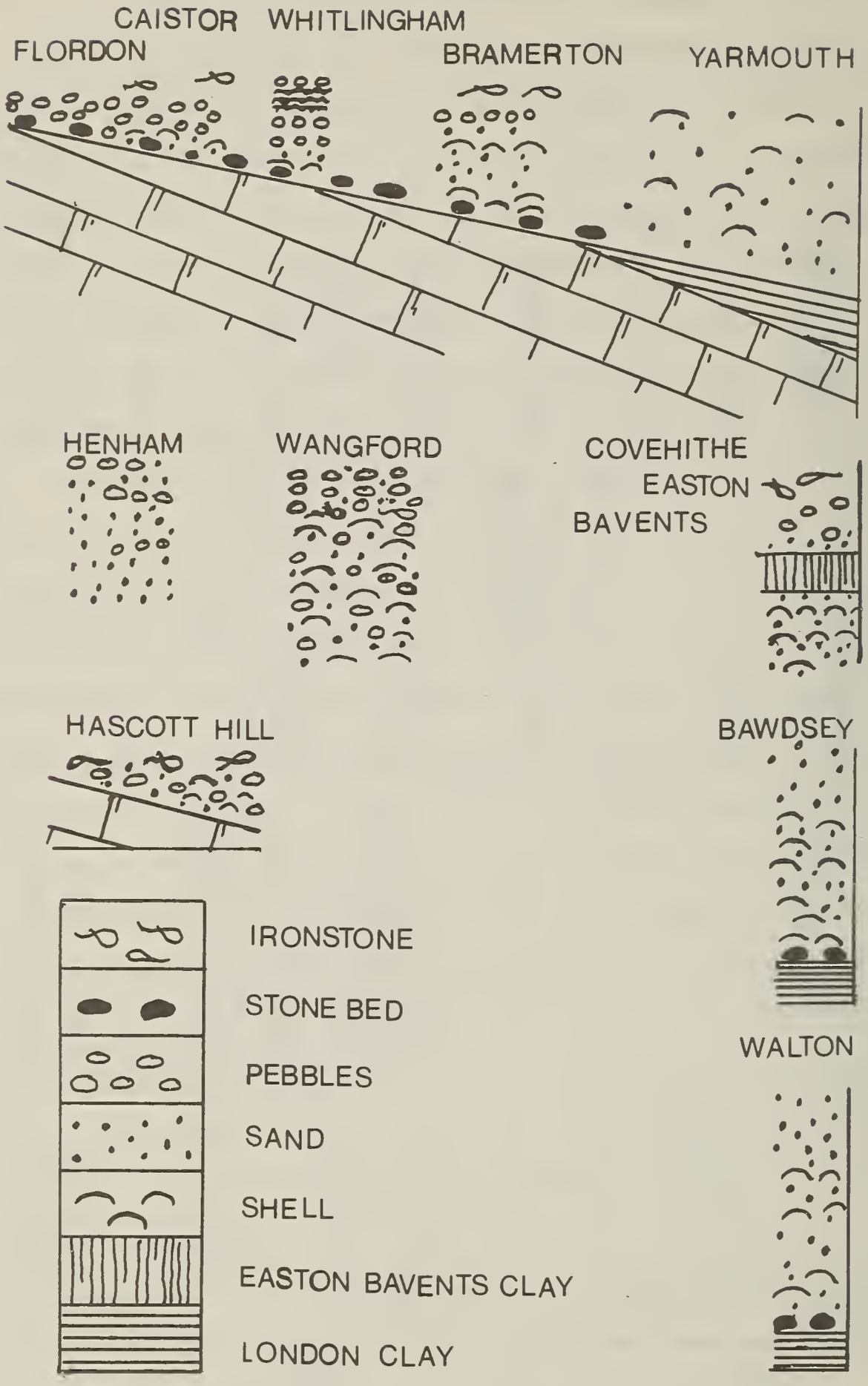

Fig. 1 Summary of the lithology of the Crags in East Anglia.

of off-shore sand-banks has been suggested, but, like the Diestian of Belgium, it may well prove to have filled a trough in the sea-floor, with subsequent, preferential erosion of the surrounding material. The NE-SW alignment of the main axis of the mass is similar to other troughs containing later Crag deposits at depth.

The Coralline Crag consists of cross-bedded, shallow-water, calcareous, marine sands, with a very rich fauna. Occasional small phosphatic nodules occur. At the surface the colour is yellowish-white, occasionally stained red where in contact with the Red Crag, but at depth has a greyish-blue colour. The upper part of the series, the Rock Bed Facies, is partially decalcified and reconsolidated to form a soft, friable rock in which fossils with calcitic composition, such as pectens, echinoids and polyzoans are prominent.

Red Crag Series (Waltonian,Newbournian and Butleyan)

Lithologically the whole of the Red Crag series is similar, consisting of shelly, quartzose sands with subordinate clay and silt layers with redeposited iron oxide. From the base upwards, four types of sedimentation occur:

1. Basal Nodule Bed, occupying hollows in the London Clay and containing numerous phosphatic nodules, large irregular flints and a variety of derivative fossils.

2. Impersistent, fine quartzose sands, apparently deposited in quiet water.

3. Strongly current-bedded sands, representing migrating submarine dunes, with occasional shell platforms, flaser beds, diapirism and other structures. Minor nodule beds sometimes occur. Shells are either scattered through the sands or occur as definite shell seams, often

with one species predominating.

4. More or less horizontally bedded shelly sands passing up into decalcified sands.

The typical reddish colour is due to oxidisation of iron and, at depths, these sands are also a greyish-blue colour. The contained fossils show that there was considerable reworking of earlier beds throughout the period of the Red Crag.

Norwich Crag Series

A more variable series of shelly sands, clays and pebbles. The Chillesford Beds, resting on typical Upper Red Crag at Chillesford, and on Coralline Crag at Aldeburgh, are considered part of this series, although the lowest beds, the *Scrobicularia* Crag, are completely atypical of the Norwich Crag both in fauna and in the fact that it consists largely of reworked Red and Coralline Crag.

Shallow water facies of the Norwich Crag, such as the Westleton Beds, consist almost wholly of well-packed rounded flint pebbles, similar to those of a beach. In the cliffs between Covehithe and Southwold, the Baventian Clay is usually included with the marine series, although macrofossils are generally absent. Above the Baventian Clay on the coast, in the upper part of the series in the Yare Valley, and elsewhere, are very varied deposits of sand, gravel, ferruginous clays, flaser beds etc., which are generally unfossiliferous although sometimes, as at Caistor St. Edmunds, the sands may show traces of marine boring organisms. Where seen, the base of the series is usually a layer of eroded, fairly angular flints, known as the Stone Bed.

The Cromer Series

Due to rapid lateral changes in the lithology and the continuous

coastal erosion of the present day, the stratigraphy of the Cromer Series is very difficult to follow. Typically, as at Runton, the Stone Bed, resting on the Chalk, is followed by shelly, ferruginous, marine sands (the Weybourne Crag), which in turn is overlain by a very variable series of estuarine and freshwater beds. To the west of Sheringham, recent (1976) exposures showed a pebble bed with white quartzites, resting directly on the flint Stone Bed. Within about 200 metres, the succession changed to green clays and flaser beds, then to an intraformational breccia of ferruginous clay, and finally to sands and gravels. Most of the sections, and some of the beds (such as the Yoldia myalis Bed) of early writers, can no longer be recognised due to erosion. The fauna of the marine beds of the Weybourne Crag, closely resembles that of the Norwich Crag.

The Cromer Series are followed by an arctic plant bed of the overlying Glacial Series.

The Belgian Plio-Pleistocene

As the series in the Netherlands is known only from borings, the succession around Antwerp is chosen for comparison. In the last twenty years there have been numerous temporary exposures in the building of roads, tunnels and docks and in the Metro workings under Antwerp itself. The Antwerp Neogene consists of a series of greyish blue, shelly marine sands. Glauconite is very abundant in the lower part, imparting a darker colour, hence the early name of the Black Crag of Antwerp. The amount of glauconite decreases upwards, giving a lighter colour, and there is an increase in the silt and clay content. In the pper part of the succession there are distinct shell bands. Owing to the similarity of lithology throughout, some of the series can only be

distinguished palaeontologically.

Sands of Antwerp (Anversian)

The dark-coloured, Miocene Sands of Antwerp rest on the Oligocene Clays of Boom. At the top, the junction with the next series is usually marked by a bed of bored concretions, fossil wood, whale bones etc.

Sands of Kattendijk (Kattendijkian)

Similar dark-coloured sands but with a distinct fauna, now considered to be Pliocene. Occasional layers of whale bones occur and there are rare, scattered flint pebbles.

Sands of Luchtbal (Scaldesian)

The lowest member of the Scaldesian. In the dock area this was frequently seen as a thin, often impersistent shell bed (Falun du Luchtbal), light in colour, with small pyritic cubes on some of the shells, or cementing shell fragments. It rests on an eroded surface of the Kattendijk Sands and many of the shells are worn. Polyzoans are abundant. On the other side of the river, in the Kallo area, the Luchtbal is missing but numerous shells, derived from it, occur in the lower part of the Kallo Sands.

Sands of Kallo (Scaldesian)

Can easily be distinguished from the Kattendijk Sands in the field by its lighter colour. There are two prominent shell bands (1e and 2e Coquillier). Where the Luchtbal is missing the lower of these shell bands contains derived shells and rests on a channelled surface of the Kattendijk. Several faunistic horizons are recognised, including the Horizon à Pinna, a layer rich in complete shells of this large bivalve, persistent over a large area.

Sands of Kruisschans

Shelly sands separated from the Kallo only on palaeontological grounds.

Sands of Merksem (Merksemian)

Shelly sands, often with an appearance of reworking, and a light brown colour probably due to oxidisation of the iron since this is the highest part of the succession.

Owing to the high water table, the deposits around Antwerp are permanently saturated and there is therefore less oxidisation and weathering than in the English Crag series. The deposits were laid down in fairly shallow sea but there are no signs of littoral deposits in the Antwerp area. Elsewhere in Belgium other sands occur, probably of the same age, but they are frequently unfossiliferous or decalcified with only moulds and casts (i.e. the Poederlian=Merksemian).

Overlying the main sands of Antwerp is a thin Holocene cover of polder clay, peat (showing peat cutting) and blown sands.

It should be remembered that Belgium is bilingual and that place names may be either in French or Flemish, and horizons etc. may have originally been described in either language. Some anglicisation has been used in this paper.

Subsurface deposits in East Anglia

Almost all early literature refers to shallow exposures of littoral and sublittoral facies or occasional well logs. A number of deep bores have been made to investigate the Crag in recent years and the results published. Obviously the information from borehole samples is limited. For instance it is unlikely that an area of three or four inches diameter will yield a really representative sample of the molluscs on a sea floor. Deposits of the Red Crag series were found in

the lowest part of the Stradbroke borehole but no earlier deposits.

At depth the colour of the Crags is generally a greyish blue, although samples of Norwich Crag, from below Yarmouth, contain many shell fragments and barnacle valves of a reddish colour. The fragments are too small for positive identification and it is not possible to say whether the colour is due to partial oxidisation of more or less contemporaneous material or whether this may be derived Red Crag material. Due to facies differences, and the smallness of the samples, correlation of borehole material with surface exposure faunas is difficult.

The state of preservation in the boreholes is much more favourable to the survival of microfloras and various pollen assemblages have been described as biozones. These have not yet been adequately correlated with outcrop exposures, where pollen is generally poorly preserved, and no intercalated terrestrial deposits occur. The only really representative flora and fauna is in the non-marine Upper Freshwater Bed (Cromerian) of the Cromer Series, but this is younger than any of the marine Crags.

Correlations

The lower parts of the East Anglian and Continental Crags are similar and some correlations are obvious. Owing to a lack of recent literature much outdated material appears in English publications. As examples, a recent paper refers the St. Erth Beds to the "Boytonian" and in another paper the Lenham Beds are stated to be of the same age as the Coralline Crag.

Miocene

English textbooks frequently state that the Miocene Formation is not represented in Britain. In fact at least two Miocene faunas are known but require description. At Lenham, ironstones in fissures in the

Chalk yielded a suite of molluscan casts which were originally compared with the Diestian of Belgium, believed at that time to be Pliocene in age. Since then the Diestian has been shown to belong to the top of the Upper Miocene. Some of the molluscs, especially the bivalves, have a long range in time, some being still represented in the Recent fauna, and this fact must be borne in mind. At Lenham, one of the most characteristic fossils is the bivalve Anadara diluvii (Lamk) found throughout the Upper Miocene of Belgium, but the genus does not range further than the Miocene in the North Sea area.

The other Miocene fauna is found in the Boxstones - rounded pebbles of derived, dark brown, sandstone, found in the Basal Nodule Bed of the Red Crag. There are collections from the Boxstones in many museums but the species are commonly misnamed and the fauna requires description. Species so far named, in the author's collection, include:

Sinodia polytropa (Anderson)	Ficula condita (Brong)
Panopaea menardi Deshayes	Carcharodon megalodon Ag
Glycymeris sp	Laevicardium

Kattendijkian

There seems no evidence that the Lower Pliocene was ever represented as a marine deposit in East Anglia. No derivative fossils have been noted from the Coralline Crag, and typical Kattendijk fossils, such as Astarte corbuloides Lajonk are unknown.

Coralline Crag/Luchtbal

There is an almost complete agreement between the two faunas, both in species and in general composition. Polyzoans are abundant. Pseudamusium gerardi is the most typical fossil. There has been a tendency in England to equate the Coralline Crag with Pliocene but

comparison with the Antwerp beds shows it represents only the lower part of the Upper Pliocene. After deposition the Coralline Crag was exposed to subaerial weathering and decalcification of the upper part, and, during Red Crag times, to marine erosion, since pieces of Coralline Rock Bed are not uncommon in the Red Crag.

"Boytonian"/Kallo

Early in the history of Crag research it was realised that there was a hiatus between the Coralline and Red Crag and F.W. Harmer assumed that a bridging fauna must exist between the two, somewhere. Such a fauna was found by A. Bell, in phosphate workings on the Boyton Marshes, near Butley, containing a mixture of Red and Coralline Crag forms. In his stratigraphic tables Harmer named this the "Boytonian". Subsequently he noted that the material was actually a physical admixture of thin seams of Red and Coralline Crag from below the water level and the name "Boytonian" was dropped from his later tables.

The Red Crag contains a great deal of derived material which could have come from the destruction of Coralline Crag deposits. However, some of these species which appear to be derivative are unknown in the Coralline Crag. In fact beds of Kallo age could have supplied such species as *Angulus benedeni*, *Pecten westendorpianus* and others and were probably present in East Anglia and reworked by the Red Crag seas. The numerous Pliocene species of *Astarte* and *Cyclocardia* found in the Red Crag could have come from either the Coralline Crag or the missing "Kallo", as they are common to both, and therefore the original extent of the Coralline Crag need not have been so great. From the condition of the derived Kallo material it must have existed in a shelly sand.

Lower Red Crag (Waltonian)/Merksemsian

Once again there is a strong correspondence between the faunas. *Lentidum complanatum* is characteristic of both deposits.

Basal nodule bed, Red Crag

A similar suite of derived material probably occurs under both Lower and Upper Red Crag. The main sources are the London Clay and the Miocene, though it is unlikely that the phosphatic nodules all came from the London Clay as has been suggested. Phosphatised nodules, with a burrow described as *Tasselia ordami* de Neinzelin, occur and this burrow is known only in situ in the Sands of Kruisschans and the Sands of Merksem. Spiral nodules, originally the core of a burrow, *Gyrohelix*, also occur although their original horizon is not known. Neither *Tasselia* nor *Gyrohelix* are recorded from the London Clay so that some of the phosphatisation must have occurred in Neogene times.

Cetacean remains, vertebrae, teeth, earbones, fragments of ziphoid skulls etc., are common and may be Miocene or early Pliocene. The terrestrial mammalian fauna is rare and very fragmentary. Apart from a few Eocene specimens the majority are Upper Pliocene, probably derived from valley deposits during a marine transgression.

In the literature the Basal Nodule Bed is also stated to lie under the Coralline Crag, with a similar fauna. The original source of this idea seems to be in a description of a pit at Sutton Knoll, in Suffolk, which Prestwich described as being worked for phosphate (or "coprolite" as it was then known). For several reasons I believe this to be a mistake. At Sutton Knoll the Red Crag surrounds a small island of Coralline Crag and in the intimate association of the two

deposits the error may lie. Some of the Red Crag pits in the area contain a proportion of Coralline Crag boulders and slipped material. The site of the pit, as shown on the sketch map, was on the Rock Bed and would have meant digging through a considerable thickness of hard beds. This would have been completely against the normal practice when working the nodules, which was to locate an outcrop on a valley side and follow the bed inwards until the cost of removing the overburden became prohibitive. One of the fields next to the knoll is still known as the Coprolite Field and shows numerous nodules from the base of the Red Crag and would have been the obvious place to work the deposit. Just across the valley, at Ramsholt cliff, the Coralline Crag may be seen resting on the London Clay with no sign of a nodule bed between, nor has one been recorded anywhere else where the bottom of the Coralline Crag has been reached. If such a nodule bed existed it seems strange that no derived material occurs in the Coralline Crag itself as it often does in the bulk of the Red Crag. Small, rounded isolated phosphatic nodules do occur in the Coralline Crag but never seem to contain any derivative fossils. Until proved otherwise it seems best to consider the Basal Nodule Bed a part of the Red Crag only.

Upper Red Crag (Newbournian and Butleyan)

There appears to be no Continental equivalent to the Upper Red Crag whose fauna differs considerably from the Lower. It is difficult to separate the two 'zones', Newbournian and Butleyan, proposed by F.W. Harmer. If a stage name is required then the term Orwellian is proposed, after the river of that name, characterised by '*Cardium*' *angustatum* and the presence of boreal species in greater abundance.

Chillesford Beds

The Scrobicularia Crag is considered by the present author to be the lowest member of the Norwich Crag Series, due to the presence of 'Cardium' angustatum and other typical Red Crag forms. It is difficult to separate the derivative material from the real fauna in these beds. The reworking of the earlier Crags, the extreme shallowness of the water, and a general reduction in the size and thickness of the molluscan shells point to radical changes.

The overlying Chillesford Crag consists of silty beds with some bivalves in the position of life (Mya) and others with the valves still joined. The fauna is typical of the Norwich Crag although the facies is not.

Norwich Crag Series

Harmer included all beds between the Red Crag and the Arctic Plant Bed in his Icenian stage. Marine and non-marine beds of this age are known in the Netherlands although an exact correlation with East Anglia cannot be made at present. Acila cobboldiae, Ptchopotamides icenicum and other typical Icenian fossils are found in the estuaries and on the beaches of Zeeland. Among the non-marine molluscs, Viviparus glacialis found in deposits of unknown age in the Bure valley, is widespread in the Tiglian of the Netherlands.

The Norwich Crag fauna is fairly similar throughout its range, although there are local variations as would be expected. Many of the species first appeared in the Upper Red Crag, though some, such as Hemirhynchia psittacea and Turritealla communis are rare in the Red Crag. In many of the sections, the upper part contains the freshwater snail Viviparus medius together with the remains of fish, voles and

other small mammals Macoma calcarea is usually common. This association is widespread, being found at Thorpe Aldringham, Covehithe Warren, Bramerton and even in the Weybourne Crag at Weybourne.

In the outcrops, the Norwich Crag is rich in littoral forms such as Mytilus edulis, Nucella lapillus, Littorina littorea and Hydrobia. Monstrous forms of some of the gastropods are found in the upper part of the deposit in the Yare Valley.

Among the more unusual fossils are fish bones showing hyperosteosis or excessive swelling. These were referred to Platax woodwardi Ag., but can be shown to belong to more than one species. The swollen cleithra have been known from Zeeland for some time and have been found recently in situ in the Sands of Merksem at Antwerp and there is an example from the Red Crag in the Ipswich Museum (R.Markham, personal comm.). Thus the cleithra have a different time range to the remaining 'Platax' bones. Some of these have a strong resemblance to the Eastern American jack-fish, Carynx hippos from Florida, and may belong to the same family. A single, elongate vertebra of the 'jackfish' type was picked up on the beach at Domburg, Zeeland where other Icenian fossils are washed up but the "butterfly bones" are only recorded from East Anglia. They are unlikely to belong to Platax which is a tropical Indo-Pacific genus.

The Norwich Crag was sometimes called the Fluvio-Marine Crag and non-marine shells are not uncommon. The bivalve Corbicula fluviatilis occurs at several sites between Aldringham and Wangford, is apparently missing in the Yare Valley, but is in the author's collection from a well at Skeyton and from the Weybourne Crag. Both land and freshwater forms are found with the marine fauna of the Norwich Crag, and perhaps

these, with the vole remains, may be accounted for by the sea occupying a series of drowned valleys or sheltered inlets, during the early part of the Norwich Crag transgression. The non-marine fauna is in need of revision, and especially of comparison with the Continental Tiglian.

The name Mammaliferous Crag was also given to the Norwich Crag and a large number of vertebrate remains are listed although many of these are known only from fragments, and indeterminate bone fragments greatly outnumber determinable material. Remains of marine animals are generally better preserved and the author has recently collected vertebrae of dolphins and a large seal, in pits in the Yare Valley. The larger terrestrial mammal remains are generally very fragmentary and the fragments are generally sharp and unrolled, even when occurring in pebbly deposits. It is probable that most of these mammal bones were already fossilised before incorporation in the marine deposits.

Cromer Series

Typical Weybourne Crag is limited in extent on the North Norfolk coast but occurs in a very disturbed condition at Weybourne, under the modern beach deposits at Runton, and on glacially moved Chalk rafts at Overstrand etc. The fauna is essentially similar to the Norwich Crag including '*Platax*', vole remains, *Viviparus medius* and *Corbicula fluminalis* but is distinguished by the addition of abundant *Macoma balthica*. The latter species is characteristic of large estuaries the sheltered inlets at the present day and prefers a muddy sand.

Elsewhere on the coast, where there is no overlying Weybourne Crag, the Stone Bed often contains little but broken examples of *Mya*

and Arctica islandica. The estuarine sands of the series sometimes contain marine shells. Thus sands on one of the Chalk rafts at Overstrand contained large numbers of valves of Mytilus edulis. Layers of flat hardened mud pebbles occur, weathering a reddish-brown, and may be picked up on the beach in large numbers. These contain shell fragments including Cardium, fragments of freshwater shells, plant remains and an example of the polyzoan Flustra foliacea, an assemblage typical of an estuary.

Inland the status of the marine beds of the Cromer Series is not clear. In the Bure Valley early memoirs record sands and pebble beds, the upper of which contained Macoma balthica and the lower did not, but the pits are now all overgrown and require re-excavation. As mentioned, a well at Skeyton recently yielded a small fauna which included M.balthica, Corbicula fluminalis,Boreoscala greenlandicum, Littorina littorea,Cardium edule,Mya arenaria and Arctica islandica.

Marine Temperatures

In the North Sea there was a general cooling from the tropical deposits of the Eocene to the cold of the Glacial series. The Plio-Pleistocene deposits of Iceland record between six and eight glacial cycles large enough to have caused sea-level changes, before the Anglian. It has been suggested that the large, unworn flints, resting on the London Clay, below the Red Crag, were ice transported to their present position ten miles from the Chalk outcrop. The records of igneous erratics and striated flints found in the Red Crag have never been backed by photographs, or specimens, and may have been accidentally introduced into the Red Crag pits. The most positive evidence for pre-Anglian cold periods are the ice wedges in sands in the Cromer Series.

No purely cold water molluscan assemblages are known from the East Anglian Crags. Harmer believed there was a progressive cooling throughout the Red Crag period, culminating in the Butleyan and based on an increasing number of boreal species. However, 'southern' species such as Calyptraea chinensis are found in the same deposits. In fact marine temperatures may not follow terrestrial conditions and may be influenced more by water currents. The upwellings of cold water on the Californian coast are an example of this sort of control and the warming effects of the Gulf Stream on Iceland another. The apparent paradox of "hot" and "cold" species occurring together might be explained by influxes of northern Pacific genera which are known to have occurred, allowing a southward expansion of "cold" species. Many of the genera originated as Pacific boreal forms and entered the North Atlantic and North Sea when there was free access between the two oceans. It would imply no land bridge in the Bering Sea and a warmer Arctic Ocean and it can therefore be argued that boreal forms can actually indicate a warmer climate.

Such influxes occurred in the Miocene, Upper Pliocene and Lower Pleistocene. The genera Neptunea, Nucella and Panomya, among others appear in the Kallo for the first time. By the start of the Upper Red Crag period many Pliocene forms died out and were replaced by new boreal forms, such as Astarte montagui, Acila, Anomalosipho etc.

Land molluscs in the Crags do not indicate low temperatures. Helicigona lapicida from the Butleyan would indicate a temperature no colder than the southern half of Britain; Corbicula fluminalis which is found in the Norwich and Weybourne Crags is generally considered a good indicator of warm conditions, being associated with Hippopotamus in the Interglacials, and at present living in the Nile.

Recently the author has discovered shells of a slug, Parmacella, a Mediterranean species, in the lower part of the Norwich Crag at Bramerton and F.W. Harmer figured an example of Otala lactea from the Red Crag.

If this view is correct then the land molluscs indicate warm or temperate conditions. Rising temperatures which allowed passage through the arctic seas for molluscs would also cause a general rise in sealevel and therefore local transgressions. The periods of maximum transgression, such as the Upper Red Crag and the Norwich Crag could represent maxima of temperature. Conversely, minima would result in lowering sealevel and regression such as occurred in the Upper Pliocene when the Coralline Crag was exposed to weathering, or during the shallowing and reworking that occurred during the deposition of the Scrobicularia Crag. This hypothesis is based on there being no large scale tectonic movements in the area. The apparent occurrence of small deposits of Red Crag at Netley Heath etc. up to 600 feet above sea level needs further investigation. It is not certain whether the ironstone was transported to its present position. The determination of molluscan casts is always difficult and there is the possibility that like the Lenham Beds these are pre-Crag in age. Thus the Sylter Crag of Germany, identified as Waltonian from the molluscan casts, was shown to be Upper Miocene in age.

Extent of the Crags

Fig. 2 shows a diagrammatic indication of the extent of the various Crags in East Anglia. Harmer suggested a progressively northern infilling of a Series of bays during the Red Crag, and that no two of his "zones" were seen in conjunction. The upper Red Crag as a whole, is higher than the Lower, reaching the present 150 ft contour at Sudbury,

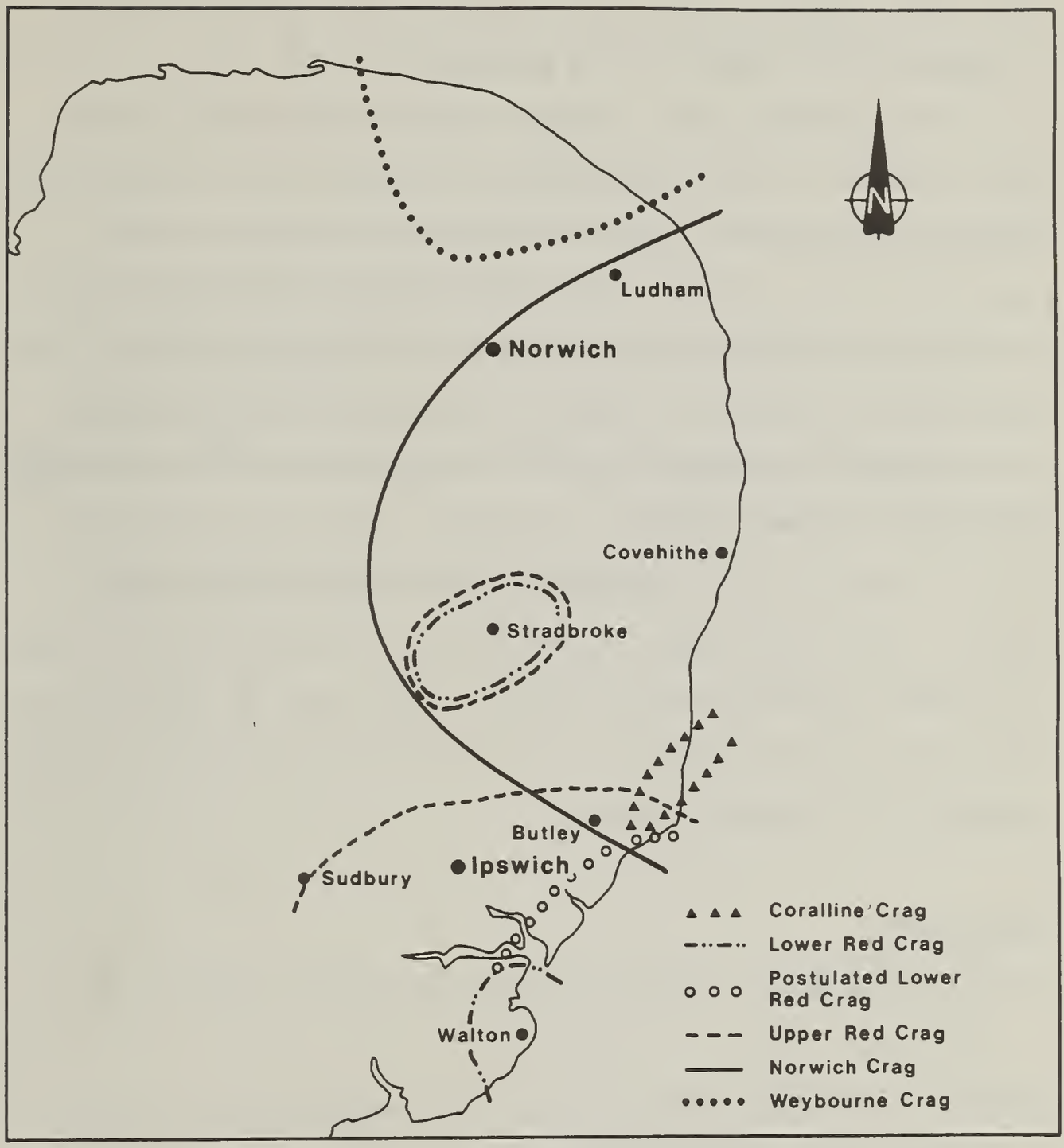

Figure 2. Distribution of the crags.

Hascott Hill etc. The extent of the Waltonian may be somewhat greater than Harmer surmised. There have been persistent reports in the old literature of beds similar to the Waltonian occurring in the base of pits in the Newbourne area. A study of material from Boyton Marshes shows a mixture of forms from the Coralline Crag, from the Butleyan and, quite unexpectedly, typical Waltonian fossils. Unless these were mixed by the collector, which seems unlikely, there may be traces of Waltonian in several places, and that the Waltonian beds, being topographically lower, have been mainly destroyed by modern erosion. The transgression associated with the Norwich Crag series also reaches the present 150 foot contour.

For those who live in the low levels of Norfolk there is the not very comforting thought that eventually, if the North Sea continues its present destructive erosive efforts, it may reach its highest Crag levels again with the valleys of the Yare and the Bure becoming drowned estuaries like those near Ipswich.

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Bull. Geol. Soc. Norfolk, 29, 46-55 (April 1977)

SEDIMENTS FROM HOLKHAM BEACH, NORTH NORFOLK COAST

W.I. ORONSAYE*

Introduction

The variety of agents at work on the Norfolk coast (such as waves, tides and wind) and its constant changes in response to erosion and accretion have made it an excellent area for those interested in studying coastal processes. Because of similarities in the processes along this stretch of the coast (from Cromer to Hunstanton), many workers have found it more convenient to group the whole area as a unit when studying the morphology and historical development of the entire Norfolk coast. This may be one of the reasons why there is a very limited amount of information specifically on such areas as Holkham Bay.

Apart from the works of Steers (1938, 1960, 1961, 1971) and the brief mention of Holkham Beach in the works of Purchas (1965) and Clayton (1975), it is surprising how little information is available on the geology of such a vital area of this coast. The present paper has grown out of a research project that I have been carrying out in Holkham Bay since 1974.

Brief Description of Area of Study

Holkham Beach is situated on the North Norfolk coast between Burnham Overy Staithe and Wells-next-the-Sea. Like the entire North Norfolk coastline, the above section is orientated East-West. The North Sea lies due North of the shore line and no other land intervenes

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between the study area and the North Pole! The beach is approximately 3000 m long, and reaches a maximum width of about 1,500 m at low spring tide. The landward side of the beach is edged by a series of dune ridges known locally as the "Holkham meals". These dunes extend eastwards in an arcuate form as far as Wells and in an unbroken line westwards to the eastern side of Burnham harbour. (See Figs. 1 and 2).

Hydrodynamic processes affecting the morphology of the beach

Waves and longshore currents are the main sources of hydraulic energy on the shores of Holkham Bay. Marked changes in beach profiles indicate that the sediments are moved extensively by wave action and the frequently occurring sandbars and runnels around this area are evidences of longshore currents. (Fig. 2 & Plate 1) Waves with periods up to 15 seconds were recorded in the Bay. Waves of longer periods are generated in the open sea and their propagation into the Bay is controlled by the angle of approach and the bottom topography of the area. Summer storms are uncommon, while storms are common and waves are strongest in winter. Maximum wave energy is generated in the winter by waves whose periods range between 8 seconds and 12 seconds. Waves in Holkham Bay are generated by onshore winds and are only modified by the local winds. Thus swell of considerable amplitude and energy may occur in this area in the absence of local winds. The prevailing wind which is from West to East does not affect the littoral movement, but the dominant winds which are from the N.E. have much more powerful influence on th e movements of pebbles and the general movement of longshore drift.

Tides within the study area are semidiurnal. Reconnaissance studies reveal that the beach sand level is shifted not only by the daily change of tide, which shifts the zone of breakers away from and

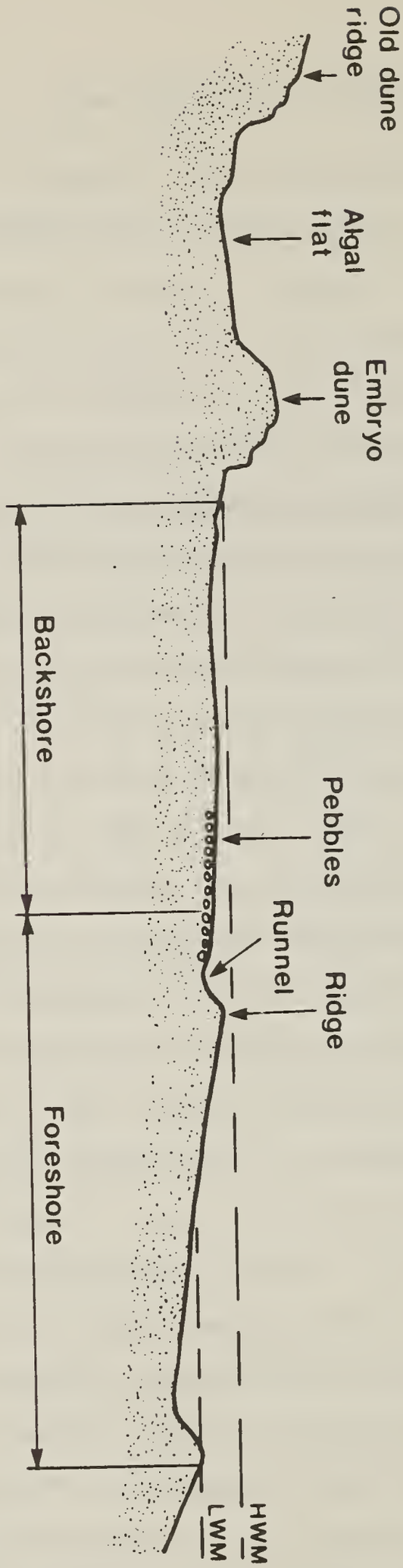

Figure 1. Holkham Beach Profile (not to scale).

towards the shore, but is affected more markedly by the change from Spring to Neap and from Neap to Spring tides.

Sediments and sedimentary structures

(a) Gravel Beach: As there is no source in the area from which the shingle on this beach could have been derived, it follows that all the pebbles found on the beach must have been transported here by waves or tidal currents from the sea or from other distant beaches. According to Steers (1954) it is evident that most of the shingle and gravel deposits on the North Sea coast have been derived from the vast quantities of stones scattered in boulder clays during the ice-age, which at present covers the floor of the North Sea.

It is obvious from experiments carried out on pebble movements on the beach, and from reconnaissance studies, that waves and not tidal currents are responsible for shingle movement along the beach. The gravel beach rises topographically above and rides laterally over the beach face towards the high water level, and is only reached by Spring tides. Thus it seems unlikely that ordinary wave energy ever attains a sufficient intensity to affect it, except during exceptionally heavy storms.

(b) Sand Beach: Holkham beach possesses a convex beach slope and a uniform distribution of fine grained sand over its upper as well as its lower parts. This configuration has resulted from continuous addition of fine grained sand to the beach by progressive shorewards migration of sand ridges. This process has also, with time, completely buried a once existing back beach gravel accumulation under the sand.

The intertidal sediments in Holkham Bay are medium to fine grained

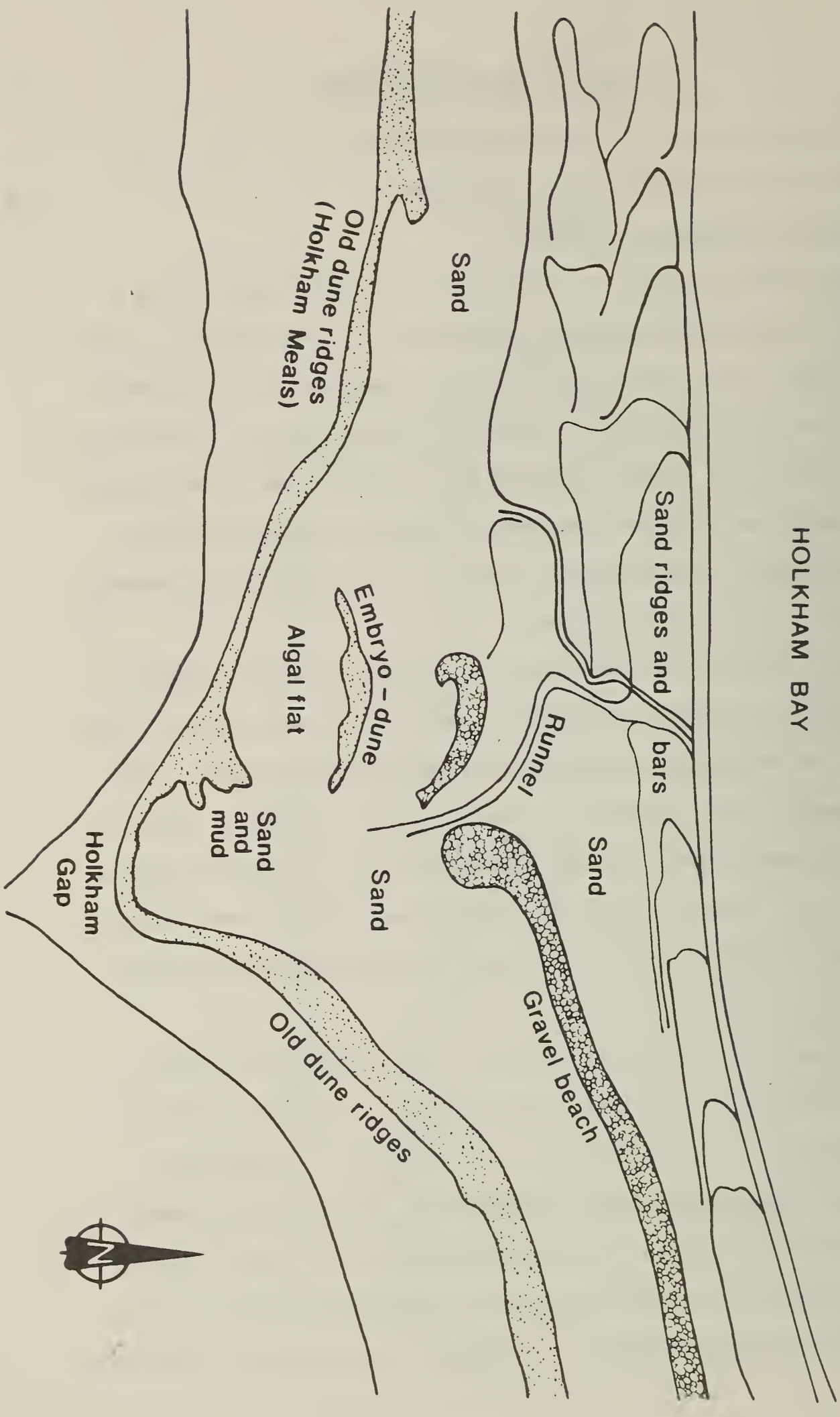

Figure 2. Sediments of Holkham Beach.

Plate 1. Aerial photographs of Holkham Beach taken by the Cambridge University Aerial Photography Department, 9th January 1975.

sands, mostly well sorted. The sediments occurring at the landward end of the beach, are less well sorted than those towards the strand line, and are to a large degree the result of wind action, which winnows and separates the finer grades from the coarser materials and subsequently concentrates them in the dunes and on tops of the berm. The mean size of the sediments range from 0.87Ø to 2.04Ø. Skewness value for all the beach samples range from -0.65 to -0.06.

Table No. 1

Parameters Mean Values	Backshore zone	Foreshore zone	Dune
Mean size MZØ	2.0	1.92	2.08
Standard Deviation 0,Ø	0.35	0.40	0.25
Skewness SK_I	-0.30	-0.25	0.17

The wide variation in the mean size distribution of sediments from the beach face is related to the wide energy spectrum of the depositing agency leading to the deposition of coarse, medium and fine sand.

Primary sedimentary structures are plentiful in the intertidal flat in Holkham; they include erosional structures (scours, crescent scour, rills and sand shadows) transport and depositional structures (current and wave ripple marks, interference ripples, streaming and parting lineations, and runnels) and some post-depositional structures (sand burrowers, raindrop impressions, textured surface, and foam impressions). These are frequently occurring during the low tide period when the beach face is largely exposed.

(c) Algal Flat: The algal flat occurs in the upper part of the intertidal flat behind what is locally known as the "embryo-dune" in Holkham.

The flat is composed of muds and silts. Surface muds are dark brown. With depth, the mud becomes blue-grey owing to organic reduction of iron oxides to sulphides. Deposition of these muds and silt occurs at high slack water from suspended sediments settling out behind the "embryo-dune". During periods of low tides and especially during the Neap tide period, onshore winds blow and deposit sand inland and on top of the previously deposited layers of mud. This has resulted in alternate layers of sand and mud in the algal flat. The occurrence of many typical salt marsh plants just west of Holkham gap is partly due to these mud deposits and partly because there was once a drainage creek from the now reclaimed marshes through the Holkham gap. There is a growing belief that this algal flat is at the early stage of marsh growth, because the morphology of the area favours the growth of a salt marsh (see Fig. 3).

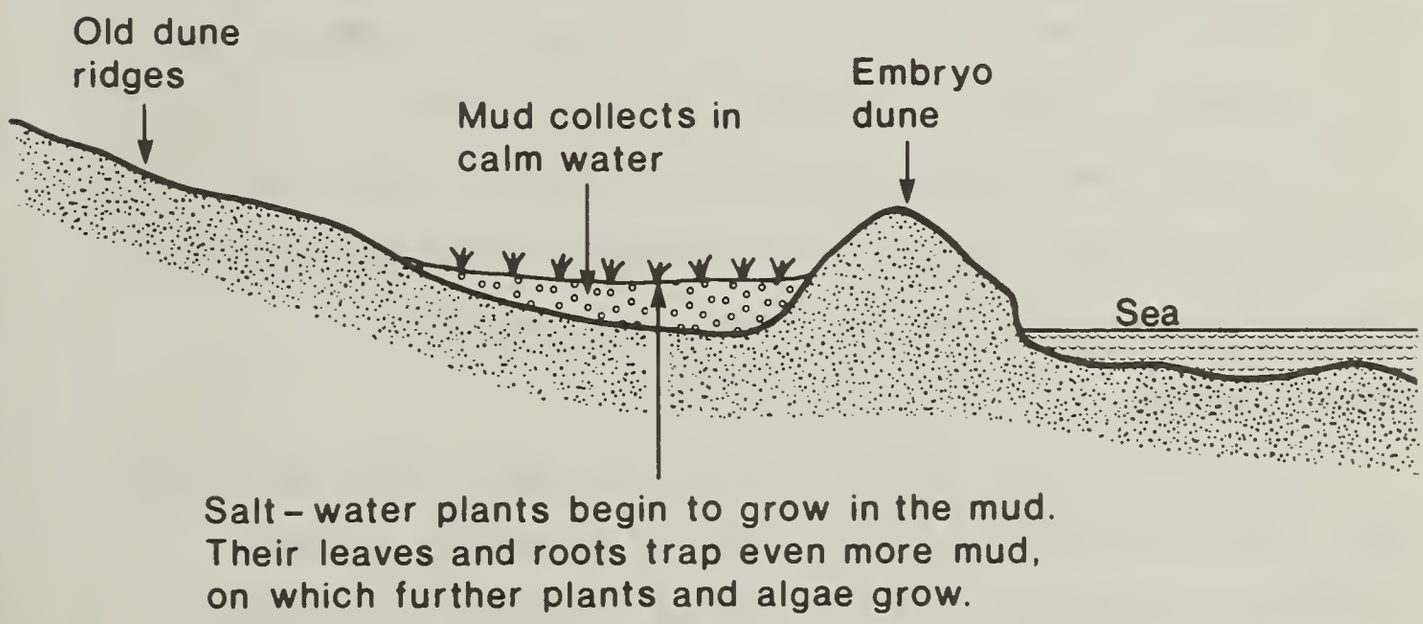

Fig. 3 Salt-marsh growth.

Conclusion

The description of the sediments has shown that three topographical features - gravel beach, sand beach, and algal flat - can be distinguished in this beach. The sediments at the landward end of the beach are less well sorted than those around the low tide part of the beach. This is because less time is available for wave action to thoroughly rework these sediments as the water retreats during the ebb tide and also, more importantly, due to the extensive winnowing of the sediments by the wind here. On the other hand, the sediments in the lower parts of the beach are better sorted because of the prolonged wave action which removes the finer materials and deposits them in the sea, while at the same time moving the coarser particles further inland as a result of the swash and backwash activity in this zone.

In addition, this work also suggests that the dunes around Holkham Bay have developed as a result of the accumulation of dried out beach sand blown from the open beach, and that this eolian process has been made possible here mainly due to the grain sizes of the sediments in the sand beach. Finally, the accessibility of the beach and the proliferation of sedimentary structures and bedforms of many types along this beach make this area a very suitable natural laboratory for the study of these structures and other coastal processes.

Acknowledgement

This work is an off-shoot of a research project (still in progress) that I am working on for a higher degree at the Geology Department, University of Cambridge. The author acknowledges financial support provided by the University of Benin, Nigeria and the Bendel State Government of Nigeria.

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Bull Geol. Soc. Norfolk, 29, 56-57

ON THE OCCURRENCE OF *Colus ventricosus* (Gray, 1839), A PROSOBRANCH MOLLUSC

T. PAIN *

This moderate deep water *Colus* is today confined to the east coast of North America, from the Grand Banks off Newfoundland to the Georges Bank off Massachusetts.

The shell is very inflated for a *Colus*, of almost five whorls, with wide, rather faint spiral cords; the aperture is large and slightly longer than the spire. Average length 55 mm. A somewhat thicker more elongated form also occurs, which Harmer (1916, 369) considered a distinct species and which he described as *Neptunea tenuistriata*. There is however no doubt that this is nothing more than a not uncommon variation of typical *C. ventricosus* and found living with it. For figures see R.T. Abbott (1974, 209, text fig. 2285) and Harmer (1916, pl. 37, fig. 1).

There is in the S.V. Wood collection in Norwich Museum a shell from the Red Crag of Felixstowe, which Harmer considered to represent *Colus ventricosus* (Gray), and which he figured (Harmer 1914, pl. 23, fig. 20). Through the kindness of Mr. P. Lawrence, Mr. P. Cambridge and myself have been able to examine this shell, and carefully compare it with recent examples of *C. ventricosus* from the Grand Banks. There is in our opinion no doubt whatever that it is a small specimen, length 32 mm and somewhat worn, of typical *C. ventricosus*, and that Harmer's identification is correct.

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Three other Pleistocene specimens have been referred to C. ventricosus. One, very imperfect, found by Harmer at Oakley, the identification of which must remain in doubt. Another from the Red Crag of Hollesley is figured by Harmer (1920, 521, pl. 46, fig. 13) and is said to be in his collection. This shell is in very poor condition, the base of the siphonal canal is apprently broken off and the surface is too worn to show any sculpture, if ever present. Its identification must remain unproven, in spite of Harmer's statement to the contrary.

The third specimen is from the Pleistocene of Bridlington, Yorks. This shell is figured by Wood (1872, 22, pl. 3, fig. 4). It is somewhat damaged, but characteristically inflated and has well preserved spiral cords and a large aperture. It can reasonably be considered an immature specimen of C. ventricosus.

The occurrence of this North American species in the British Pleistocene furnishes evidence of some connection between the two faunas, as pointed out by Harmer. However the common Colus of eastern North America, C. stimpsoni (Mörch, 1867) has not so far been recorded here.

It would seem bery probable that further examples of C. ventricosus may already be present although unrecognized in collections, or be collected in the future. It is hoped this note may persuade those concerned to keep a look out for it.

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There were five lecture meetings held during the year, one less than normal due to some last minute alterations and difficulties in getting a replacement lecture in the autumn. The meetings were: January, Dr. P.F. Wilkes, 'Some Engineering Problems Related to the Geology of Norfolk'; February, Mr. J. Eiriksson, 'Aspects of Icelandic Geology'; March, Dr. M. Leeder, 'Palaeogeographic and Economic Significance of Devonian and Jurassic River Deposits'; November, Dr. I.N. McCave, 'Deep Sea Drilling in the North-Western Atlantic : Experiences of Glomar Challenger'; December, The Annual General Meeting followed by a showing of the BP film 'Sea Area Forties' and some members' slides. All meetings were held at the University Library.

There were three Committee Meetings during the year.

I am sorry to report that due to increasing domestic and other commitments Mr. Richard Joby has found it necessary to resign from the position of Editor. Mr. Joby has been the Editor since 1971 and has been largely responsible for maintaining the standard of the Bulletin, which is generally acknowledged to be high particularly when taking into consideration the relatively small size of the Society. Grateful thanks are due to him for the not inconsiderable time and effort that he has put into the task of Editorship over the years.

As a whole the Society seems to be in a reasonably healthy state. Membership continues to grow, and even though meetings have been held at the University, with the inconvenience of transport which this causes some members, attendance at lectures has been maintained at a good level.

Once again I would like to point out that the Society exists for the benefit of its members, and I should be grateful for comments and suggestions on any aspect of Society business. The Committee meets during the year to plan ahead and, in order to maintain the Society's healthy state, it is essential that we should be aware of the feelings of the membership. Please feel free to contact any of the Committee and pass on your ideas.

This year's Committee is as follows:

Secretary	Dr. C.J. Aslin
Treasurer	Mr. P.G. Cambridge
Editor	Dr. P.N. Chroston
Field Meeting Secretary	Mr. P.J. Lawrence
Committee Members	Mr. N.E. Dean
	Mrs. E. Evans
	Mr. N.B. Peake

December 1976 Christopher J. Aslin

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The Geological Society of Norfolk exists to promote the study and knowledge of geology, particularly in East Anglia, and holds monthly meetings throughout the year.

Visitors are welcome to attend the meetings and may apply for membership of the Society. For further details write to the Secretary: Dr. C.J. Aslin, the University Library, University of East Anglia, Norwich NR4 7TJ.

Copies of this Bulletin may be obtained, £1 (plus 20p postage), from the Secretary at the address given above; it is issued free to members.

The illustration on the front cover is from Figure 80 (page 468) of the second edition of H.B. Woodward's "The Geology of England and Wales", published by G. Philip & Son, London in 1887. It is after a photograph of a Chalk pit at Whitlingham, near Norwich. The beds above the Chalk with flints, seen best to the right of the picture, comprise 4.5 to 6 m of Norwich Crag Series, made up from bottom to top of: Stone bed; False-bedded sand and gravel, with shells; Impersistent laminate clay, and shelly seam; and Pebbly gravel and sand, with seam of shells.

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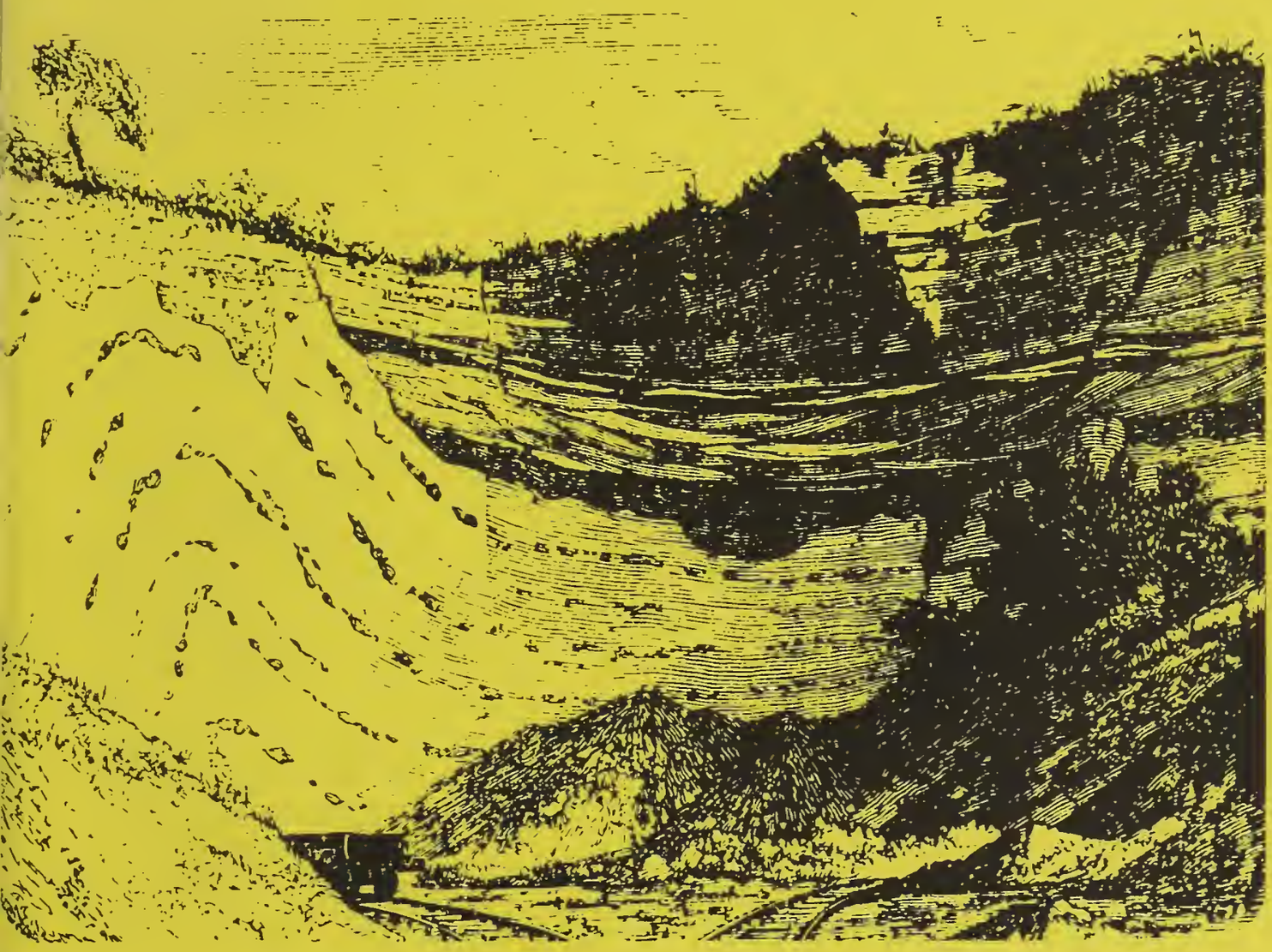
No. 30 1978



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BULLETIN of the GEOLOGICAL SOCIETY OF NORFOLK

No. 30 August 1978

Editor: P.N. Chroston

School of Environmental Sciences, University of East Anglia, Norwich, NR4 7TJ.

EDITORIAL

The Bulletin of the Geological Society of Norfolk seeks to provide an opportunity for the publication of research papers, notes, or general articles which are relevant to the geology of Norfolk in particular, or to East Anglian geology in general. The Society is also prepared to consider articles of general geological interest for publication, but normally they will be expected to include some local relevance. There are no restrictions on subject matter (apart from regional significance) and indeed a brief look at past issues will show that topics included range from environmental geology to section descriptions, from geophysics to palaeontology and from the Precambrian to Recent. Similarly there is no formal restriction on length and we welcome full length research papers, short notes, and correspondence. All papers are normally refereed.

Potential contributors should note that we prefer manuscripts to be submitted in typewritten copy, though legible handwriting is acceptable. In either case, it would be helpful if the style of the paper in terms of capitalization, underlining, punctuation etc., would conform strictly to those used in the Bulletin. The reference list is the author's responsibility alone and should be checked carefully.

Illustrations should be executed in thin dense black ink line. Thick lines, close stipple or patches of black should be avoided as

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Bulletin no. 31 will be published in Summer 1979 and contributions should be sent to me as soon as possible. I am happy to answer any queries concerning the suitability of a paper or any other editorial problem.

P.N.C.

Bull. geol. Soc. Norfolk, 30, 3-38 (August 1978)

THE PLEISTOCENE HISTORY OF WEST NORFOLK

Presidential address given at King's Lynn 21st Feb. 1977.

R.W. GALLOIS*

Abstract

The stratigraphical relationships of the various Pleistocene deposits of West Norfolk are discussed and the field evidence which enables part of the Pleistocene history of the area to be deduced is described. Three cold periods, represented by the Chalky - Jurassic till, the Lower Tottenhill Gravel and the Hunstanton till, can be recognized. These were separated by temperate periods during which the Nar Valley Beds and the Hunstanton raised beach were deposited. Comparison of the West Norfolk sequence with those of the adjacent areas of southern Fenland and Lincolnshire suggests that the Pleistocene history of the area may be more complex than has been previously supposed and that the Pleistocene deposits exposed around the edge of Fenland at the present day provide only a fragmentary record of the history of the period.

Introduction

West Norfolk is a critical area for the study of Pleistocene stratigraphy since it exposes well developed deposits of at least two glacial (the Chalky-Jurassic till and the Hunstanton till) and two temperate episodes (the Nar Valley Beds and the Hunstanton raised beach). The author's knowledge of the area stems from the IGS geological activity in West Norfolk which, in the past ten years, has included

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field surveys for the preparation of the King's Lynn/Wash (Sheet 129/145), Wisbech (Sheet 159) and Ely (Sheet 173) 1 to 50 000 scale geological maps and site investigations for the Wash Water Storage Feasibility Study and a proposed proton accelerator near Thetford.

Norfolk has gained the reputation of being the graveyard of British geology (or geologists) because of the number of Pleistocene howlers it has produced. Most of these have resulted from a limited amount of observational data being stretched over too big an area in an unruly haste to 'solve' the Pleistocene stratigraphy of East Anglia. The history of these hasty correlations now extends back over more than 100 years.

In deference to the high honour of his office the President proposed to avoid the ranks of the geological corpses and to discuss only those aspects of the Pleistocene history of West Norfolk that could be shown to his satisfaction as a field geologist to be stratigraphically unambiguous. The following account therefore describes the field evidence, such as juxtaposition of strata, nature of contacts and the general distribution and lithology of the Pleistocene deposits, that can be used to deduce the history of the area. It does not attempt to correlate the West Norfolk sequence with that of the Midlands, North Germany or the Alps by means of either fauna or flora. Nor does it refer to the British Standard Stages proposed by the Geological Society Quaternary Era Sub-Committee (Mitchell et al 1973) since the establishment of a standard sequence by adding together type sections which are geographically widely separated defies all the rules of stratigraphical nomenclature. The unsatisfactory nature of this sequence of stages is demonstrated by the assignment of the most

widely distributed glacial deposit in Norfolk, the Chalky - Jurassic till or Chalky Boulder Clay, to the Anglian stage (op. cit., Table 2) in the eastern part of Fenland and the same deposit to the Wolstonian Stage (op. cit., Table 3) in the western part.

The sequence of Pleistocene deposits in West Norfolk and their correlation with the adjoining areas of southern Fenland and south east Lincolnshire are shown in Table 1. The evidence on which this sequence is based is discussed below.

Chalky-Jurassic till

The oldest Pleistocene rocks in West Norfolk are the Chalky-Jurassic till (Chalky Boulder Clay of some authors) and associated sand and gravel. These deposits infill a topography cut into the solid deposits and are made up almost entirely of Upper Jurassic and Cretaceous rocks derived from Lincolnshire and Norfolk.

The Chalky-Jurassic till of West Norfolk now occurs as dissected remnants of what may originally have been an almost continuous deposit (Fig. 1). Thick till sequences are confined to deep valleys in the rock-head surface: thin patches of till occur on the interfluves and on some valley sides. In West Norfolk there are places where valley till is continuous with that extending across the interfluves and there is no evidence to suggest that more than one phase of deposition of Chalky-Jurassic till occurred.

The Chalky-Jurassic till is everywhere characteristically composed of slightly sandy clay with fine and medium gravel-sized erratics of chalk (usually more than 90%), flint, Upper Jurassic cementstone and shale, Lower Cretaceous sandstone and ironstone, Red Chalk, Carstone and rare farther-travelled materials. The lowest part of the till is

Table 1 Correlation of the Pleistocene sequences of West Norfolk and adjacent areas

Deposits			Approximate age in years before present	Presumed sea-level relative to present	Erosional features in West Norfolk
West Norfolk	Southern Fenland	Lincolnshire and Holderness			
Solifluction deposits and periglacial features	Solifluction deposits and periglacial features	Solifluction deposits and periglacial features	10,000 to c15,000	rising from -100 to -30m	formation of meltwater valleys (well seen in chalk outcrop)
Hunstanton till and associated sand and gravel; Hunstanton scree deposit	'Fen-edge gravels' including Terrace 1 of rivers Gt Ouse and Cam; Wretton Terrace of R Wissey	Drab, Purple and Hessle tills and associated sand and gravel	c15,000 to c46,000	-100m 'Fen -edge gravels' graded to levels of postulated glacial lake	?formation of Fenland 'islands'
Hunstanton raised beach; ?upper part of Tottenhill Gravels	? March Gravels	Sewerby raised beach;	>46,000	+ 3 to + 5 m	formation of Hunstanton buried cliff
lower part of Tottenhill Gravels	Higher terraces of rivers Cam and Ouse	?Basement till of Bridlington:			extensive erosion of earlier Pleistocene deposits
Nar Valley Clay	?salt marsh clay at March			rising from -8.5 to +30m	
Nar Valley Freshwater Beds	Higher terraces of rivers Cam and Ouse			rising from -20 to -8.5m	
Varved clays passing down into Chalky -Jurassic till with associated sand and gravel deposits	Chalky -Jurassic till with associated sand and gravel deposits	Chalky -Jurassic till with associated sand and gravel deposits		-100m	modification of fluvial valleys; formation of scour hollows and tunnel valleys
preglacial weathering products				falling from 0 to -100m	preglacial valley system

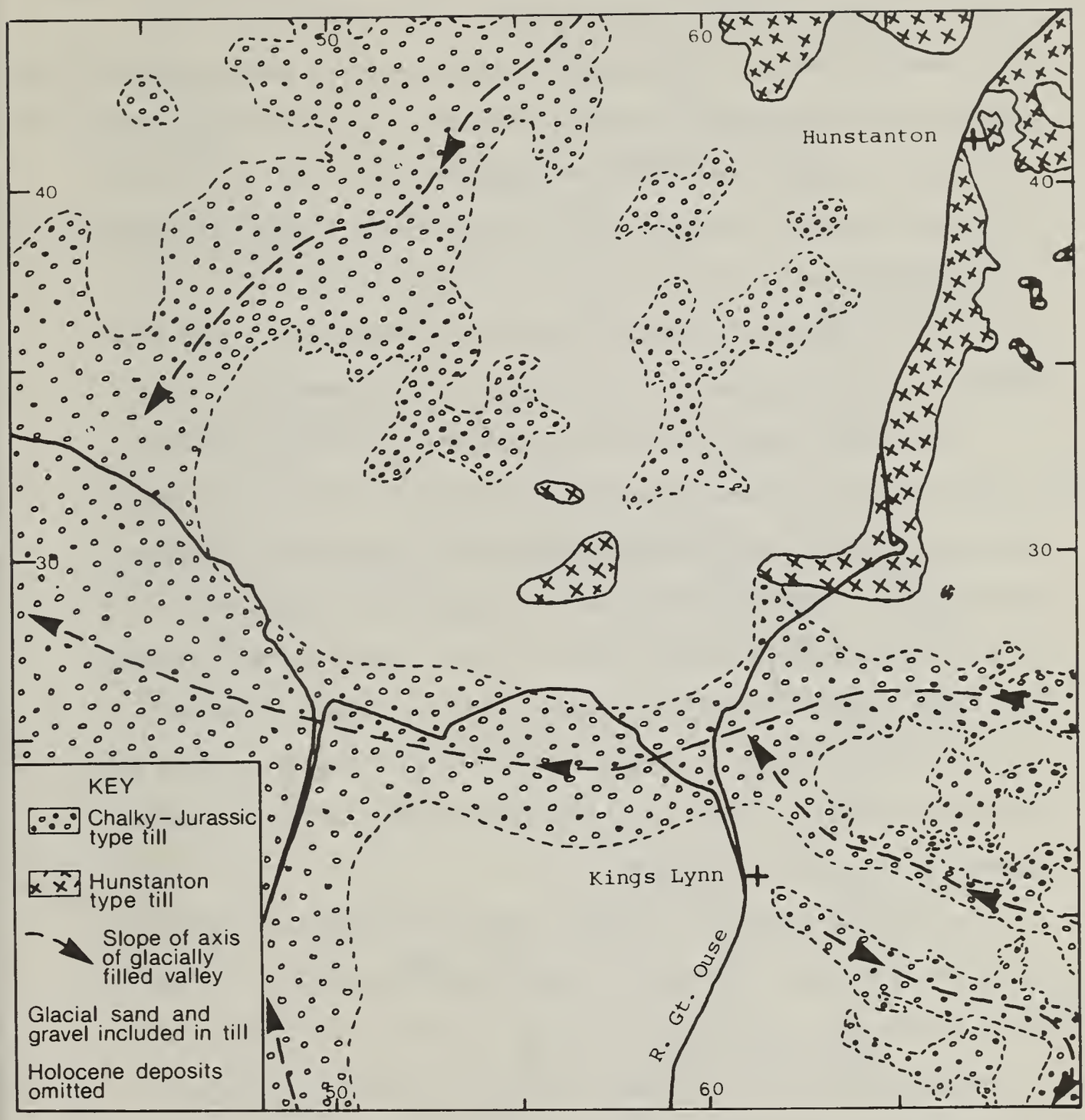

Fig. 1 Distribution of glacial deposits in N.W. Norfolk and the S.E. part of the Wash (after Gallois 1978).

commonly rich in locally derived materials. On the Upper Jurassic and Lower Cretaceous outcrops dark grey clayey tills, derived from the Upper Jurassic and containing Jurassic cementstone and Lower Cretaceous erratics, are overlain by paler grey, more calcareous clays rich in chalk and flint erratics. Evans (1975) has suggested that this lithological difference indicates a readvance of an upper (chalky) till ice across a stagnating lower till ice. In many sections however there is no sharp junction between the two till types and it seems likely that the lower till merely represents a basal layer of slow moving ice.

The erratic content of the Chalky-Jurassic till of West Norfolk suggests derivation from the north-west, from the broad Upper Jurassic clay vale lying between the escarpments of the Lincolnshire Limestone and the Chalk. A more westerly source would have included more Triassic and Lower and Middle Jurassic rocks. A more northerly source would have included more flint from the Middle and Upper Chalk and could not have provided the Upper Jurassic clays since these rocks have only a very limited outcrop in the North Sea (see IGS Sub-Pleistocene Geological Map, 1974 for details).

On the eastern edge of Fenland, between Dersingham and Denver, the Lower Cretaceous escarpment is broken by four east-west valleys whose floors and sides are cut in Chalky-Jurassic till (Fig. 2). At present these valleys carry small streams, the Babingley River, the Gaywood River, the Middleton Stop Drain and the River Nar. The extent of the glacial deposits in their floors and sides suggests that these valleys and streams were formerly much larger.

The glacially-filled Babingley valley rises near Great Massingham (TF 780 210) and from there can be traced westwards, via boreholes

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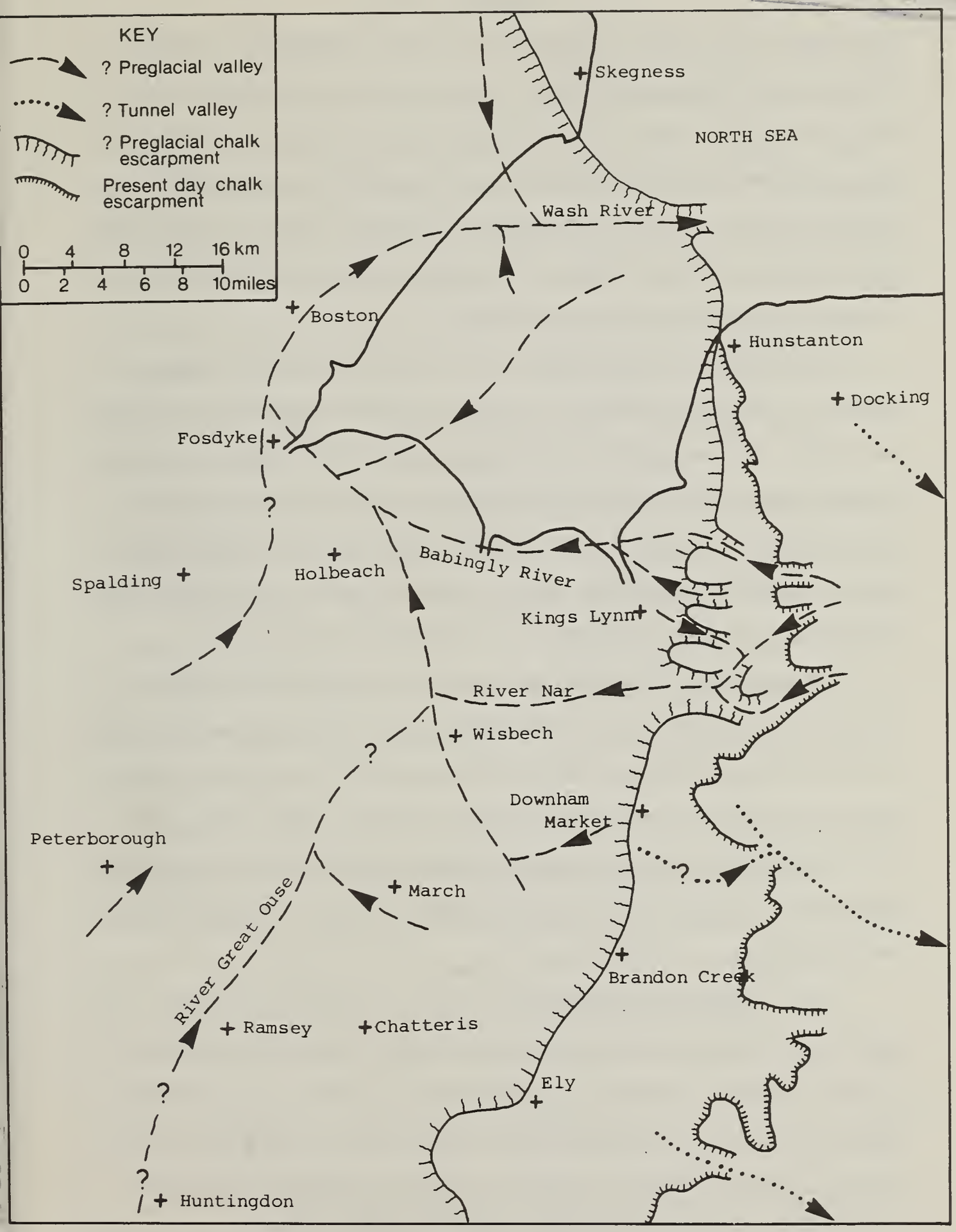

Fig. 2 Possible preglacial and subglacial valley systems in West Norfolk and the adjacent area (after Gallois 1978).

that proved thick glacial deposits at Grimston (146/404a)*, Congham (146/8) and Hillington (145/73a), to the present day Babingley valley at Castle Rising. West of Castle Rising the valley passes beneath the Recent sediments of the marshlands and its course is presumed to continue almost due west via boreholes at Vinegar Middle (TF 6092 2505) and Ongar Hill (TF 5767 2444) until it meets another glacially-filled valley in the vicinity of the River Nene.

The glacially-filled Gaywood valley can be traced from Roydon Common (TF 690 218) southwards and then westwards beneath the valley of the present day Gaywood River to Gaywood Bridge (TF 638 214). West of Gaywood Bridge, the course of the glacially-filled valley is hidden by Recent deposits. There is insufficient borehole data to indicate its position beneath the northern part of King's Lynn but it probably turns northwards to become a tributary of the Babingley valley.

The glacially-filled Middleton valley lies beneath the present valley of the Middleton Stop Drain and is well defined between Fairstead (TF 645 190) and Middleton Towers Station (TF 670 180). West of Fairstead, its course is lost beneath Recent sediments under King's Lynn; east of Middleton Towers, it rapidly broadens until, at East Winch, it merges with a broad outcrop of glacial deposits which is connected to the Nar valley.

In the Cretaceous outcrop area, where it can best be studied, the glacially-filled Nar valley is the longest and broadest of the valleys in West Norfolk. The start of the glacially-filled valley is hidden beneath the thick glacial deposits of the boulder clay plateau in the area of Litcham (TF 886 177) and it is not known whether or not the

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* Institute of Geological Sciences Well Catalogue number.

valley is a closed basin. West of Litcham, the course of the valley is well defined by wells at Lexham (146/20) and Castle Acre (146/194 and 146/238), from where it can be traced to Narford (TF 765 140). Westwards from Narford its course beneath extensive spreads of Pleistocene and Recent deposits is uncertain but it probably turns north-westwards at Narborough and then south-westwards at West Bilney and passes beneath the Recent deposits of Fenland near Blackborough End. Boreholes at Wiggenhall St Peter (TF 6030 1319), Lordsbridge (TF 5704 1244), Spice Chase (TF 5513 1292) and West Walton (TF 4913 1316) show its course to continue westwards from Blackborouth End to the Nene.

The positions of other glacially-filled valleys in Fenland are largely conjectural because of the scarcity of boreholes in the area.

The present day River Wissey follows the course of a drift-filled valley that appears to be locally up to 70 m deep between West Tofts and Stoke Ferry. A tributary valley may join the main valley at Stoke Ferry and from there run westwards to join a small glacially-filled valley at Fordham (TL 617 999).

Between Fordham and Littleport site investigation boreholes show that Upper Jurassic clays are everywhere present at shallow depth beneath Fenland. The lower reaches of the rivers Wissey, Little Ouse, Cam and Lark, which cross this area, must therefore be postglacial features. The Cam and Lark both have well documented deep, drift-filled valleys in their upper reaches. It has been suggested that the buried valley of the Cam drained southwards and that of the Lark drained south-eastwards away from Fenland (Woodland 1970, p 540 and Plate 28).

Boreholes at Boston, Crowland, Long Sutton, March, Salters Lode and Wisbech have proved thick drift sequences which may indicate the

positions of valleys associated with a glacially-filled Gt Ouse drainage system. Horton (1970) has traced the drift-filled valley of the River Gt Ouse, which he interpreted as a preglacial valley, from Stony Stratford as far north as Huntingdon. The possible course of the drift-filled valley of the Gt Ouse beneath Fenland must be largely speculative. Drift sequences over 40 m thick have been proved at Wisbech, (site investigation boreholes) Long Sutton (e.g. 145/10 and 11), Fosdyke (144/2) and Boston (128/5).

Seismic profiling carried out within The Wash for the Water Storage Feasibility Study proved the presence of several deep glacially-filled valleys (Wingfield et al. 1978). These valleys, together with those in Fenland, have been interpreted (Gallois 1978) as part of a preglacial river system that was graded to a sea-level about 100 m below that of the present day. This system, which consisted of the Gt Ouse, Nene, Cam, Lark, Wissey, Little Ouse, Welland and part of the Trent, probably drained through a single valley which breached the Chalk escarpment in the central part of the Wash (Fig. 2).

The reasons for interpreting this drainage system as one of fluvial origin, albeit glacially modified, rather than one of wholly subglacial origin can be summarized as follows:-

(1) The glacially-filled valleys show no preferred orientation but appear to form a dendritic pattern draining towards a single outlet in the Wash.

(2) The glacially-filled valleys of the Babingley, Gaywood, Nene and Ouse rivers are closed basins with outlets only into Fenland.

(3) The cross profiles and long profiles of the glacially-filled valleys beneath The Wash can be seen, in the seismic sections, to have

gentle slopes and to show many of the subtleties of form that are associated with fluvial erosion and subaerial weathering.

(4) The lithology of the infilling material in the valleys is remarkably constant,being Chalky/Jurassic till in the lower parts and water-sorted till and varved clay in the upper parts.

(5) The contact of the till and the underlying Upper Jurassic clays is almost everywhere gradational and indicative of erosion by ice rather than by subglacial waters. Chalky till commonly passes down into Jurassic clay-rich till that rests on in situ Jurassic clay cut by polished shear surfaces.

In the area adjacent to West Norfolk, Woodland (1970) has interpreted the borehole data from the boulder clay plateau areas of central and east Norfolk as showing tunnel valleys cut in the chalk surface. Cox and Nickless (1972) have used a similar explanation to account for the extensive spreads of glacial sand and gravel in the Norwich area and Sparks and West (1965) considered the buried valley beneath the upper reaches of the River Cam to have resulted from subglacial erosion.

The apparent presence of a preglacial valley system and a tunnel valley system beneath the Chalky-Jurassic till of adjacent parts of Norfolk is not incompatible. Boreholes have proved drift-filled valleys more than 100 m deep in the area just east of the present day Nar-Wensum watershed (Woodland 1970). Such valleys do not appear to extend westwards to breach the Chalk escarpment between Hunstanton and Stoke Ferry, but rise irregularly eastwards towards the position of a former ice front (Cox and Nickless 1972). The present day watershed, between streams flowing westwards to the Ouse drainage and eastwards to the Yare drainage, approximately marks the dividing line between the areas

of presumed preglacial and subglacial drainage (Fig. 2). This line lies a little to the east of what in preglacial times must have been an impressive Chalk escarpment comparable to that of the present day Chilterns or the North or South Downs. The roots of this escarpment now occur as a belt of almost drift-free chalk separating the patchily drift-covered areas of West Norfolk from the completely drift-covered till plateau of central Norfolk. Debris from this escarpment is scattered throughout the Chalky-Jurassic till of East Anglia.

The position of the former escarpment is indicated by the presence, at a number of localities, of exceptionally large erratics within the Chalky-Jurassic till. These erratics expose parts of the local stratigraphy but lie several kilometres west of the present day outcrops of the rocks they contain. It is clear from the till matrix and smaller erratics that the Chalky-Jurassic till in West Norfolk could only have been derived from the West or North West. The large erratics are therefore likely to lie close to the original position of the escarpment.

At Rising Lodge, King's Lynn (TF 668 230) there are transported masses of Gault and Chalk which are probably hundreds of metres in length. At Leziate (TF 677 192) the till encloses an erratic of Carstone and Gault about 50 m long; at The Howdale, Downham Market (TF 617 029) there is an erratic of similar size composed of Carstone, Red Chalk and Gault; finally, at Roslyn Hole, Ely (TL 555 808) Skertchly (1877) recorded an enormous mass of Kimmeridge Clay, Lower Greensand, Gault, Cambridge Greensand and Chalk within the Chalky-Jurassic till.

Between the north Norfolk coast and Stoke Ferry the present day Chalk escarpment, although divided into two parts (a Lower Chalk and an Upper Chalk escarpment) and much lower than its southern counterpart,

lies within a few kilometres of its presumed preglacial position. It appears to have been eroded by ice moving from the north-west at an oblique angle to the escarpment. Between Stoke Ferry and Ely the former escarpment was eroded by ice rich in Triassic material debris (derived from the west) which moved onto it at right angles so that the escarpment was eroded back eastwards by over 10 km in places. This has given rise to the large embayment now occupied by Methwold and Lakenheath fens. Within this embayment the islands of Hilgay, Southery, Littleport and Ely probably mark the line of the former escarpment.

To the east of the presumed position of the former Chalk escarpment the rivers Wissey, Lark and Cam have buried valleys which have been interpreted as sub-glacial valleys draining south-eastwards or southwards (Woodland 1970, Plate 1). To the west of the former escarpment the rivers Babingley, Nar and Gt Ouse appear to have preglacial valleys infilled by glacial deposits (Fig. 2). The Chalk escarpment seems therefore to have been a temporary barrier to the ice movement and to have separated an area of predominant erosion in the west from one of deposition in the east. The preglacial valleys are interpreted as scarp-slope valleys that have suffered little glacial modification. The tunnel valleys may be former dipslope valleys which have undergone extensive modification.

An interesting problem that arises from this interpretation is the question of what was happening to the north of the chalk escarpment in north west Norfolk. If, as is suggested here, the chalk escarpment decisively influenced the flow of the ice which deposited the Chalky-Jurassic till, then one might expect to find a contemporaneous till of differing lithology in the north east Lincolnshire coastal plain and in

Norfolk north of Docking, the most northerly spillover point for the Chalky-Jurassic ice.

The Chalky-Jurassic till in the preglacial valleys of West Norfolk is generally less stony and better sorted in its upper part and, in the case of the valleys of the Babingley River, the Middleton Stop Drain and the River Nar, becomes interbedded with varved clay before finally passing up into varved clay. A gas pipeline trench in the Middleton Stop Drain valley (TF 650 174 to 668 178) showed that varved clay in the central part of the valley passed laterally, via water-sorted almost stoneless till, into heterogeneous Chalky-Jurassic till in the valley side. When traced away from the valley floor towards the interfluve the stones in this till became coarser and the till generally more heterogeneous.

Nar Valley Beds

The Nar Valley Beds comprise a lower, freshwater unit, the Nar Valley Freshwater Beds, overlain by a marine unit, the Nar Valley Clay. Their relationship to the varved clay of the glacially-filled valleys is not yet clear but it seems likely that the two deposits are conformable. Shell-and-auger boreholes drilled by IGS in the Nar valley near Setch (TF 6458 1394 and TF 6377 1435) proved fine-grained grey silty sands and silts (basal part of the Nar Valley Freshwater Beds) resting on grey silts with widely spaced laminae of reddish brown clay (highest part of the varved clay sequence). These latter passed down into varved clay. The varved clay was probably deposited in a series of small ice-dammed lakes during the retreat phase of the glaciation which produced the Chalky-Jurassic till. The Nar Valley Freshwater Beds, from which Stevens (1960) obtained a flora indicative of an ameliorating

climate, may therefore represent the last stages of that glaciation and the early stages of the subsequent interglacial stage.

The Nar Valley Clay consists of finely laminated marine clays, silts and silty clays and has been proved at outcrop (Stevens op. cit.) and in boreholes to overlie the Nar Valley Freshwater Beds. In the lower part of the Nar Valley the base of this marine clay in the IGS boreholes at Setch and in Tottenhill Gravel Pit (TF 633 115) is marked by a shell bed composed almost entirely of large oysters which rests disconformably on freshwater peat of the Nar Valley Freshwater Beds. The age of both the peat and the oyster bed have been shown by radiocarbon dating (samples IGS C14/129 and IGS C14/222) to exceed 46,000 years. In the central part of the Nar Valley near Setch the junction of the marine and freshwater sequences is at about 8.5 m below O.D. Traced towards the valley sides the junction rises to about 4 m above O.D. at Tottenhill and 2.0 m below O.D. at Setch village. The junction rises eastwards as it is traced up the valley and is at more than 6 m above O.D. in the valley side at Horse Fen, West Bilney (TF 692 142) (Stevens 1960, p. 295) and at about 13 m above O.D. at East Winch (TF 705 116) (Young _in_ Institute of Geological Sciences 1972, p. 23).

The Nar Valley Clay has yielded a rich fauna of bivalves (see Whitaker _et al_. 1893, pp. 84-85 for details) which indicate a slightly brackish marine environment comparable to that of the present day Wash. The clay was clearly deposited during a period of rising sea level in a sea which transgressed eastwards across the Nar Valley Freshwater Beds and older Pleistocene deposits. Exposures of undoubted Nar Valley Clay have been recorded at heights up to 24 m above O.D. in the Narford area which suggests a minimum sea level at least 30 m above O.D. at the time

of maximum extent of the transgression if later isostatic or other differential land movement is assumed to be absent. Sparsely stony clays mapped as Nar Valley Clay by Whitaker et al. (1893, p. 89) in the Ashwicken area (TF 698 188) at heights greater than 30 m above O.D. have been re-interpreted by the present author as water-sorted till.

Stevens concluded (op. cit. pp. 291) that the flora of the Nar Valley Beds show a climatic optimum to have been reached during the latter part of the period of deposition of the Nar Valley Freshwater Beds. This suggests a rapid return to temperate conditions in West Norfolk after the retreat of the Chalky-Jurassic till ice since the field evidence indicates a rise in sea level of at least 30 m after the optimum.

Before considering the events which followed the deposition of the Nar Valley Clay it is convenient to move to the north Norfolk coast to examine the field relationships of West Norfolk's other till, the Hunstanton till.

Hunstanton till

The outcrop of the Hunstanton till is confined largely to low-lying ground along the north Norfolk coast and the eastern edge of The Wash between Hunstanton and Wolferton (Fig. 1). It is everywhere thin (probably less than 10 metres) on the land area in West Norfolk. Glacial sand and gravel deposits associated with the till extend over a larger area than the till and include the famous esker at Hunstanton Park and well developed kames and a possible collapsed esker in the valley of the Heacham River.

The Hunstanton till is characteristically a dull reddish brown sandy clay, in which the red colouration is thought to be largely derived

from Triassic marls, containing chalk and flint erratics together with a large percentage of Bunter pebbles, Carboniferous sandstones and coals, schistose and gneissic metamorphic rocks and a variety of igneous rocks. Among the more easily identifiable igneous rocks are Whin Sill dolerite from northern England and rare rhomb prophyry from Norway. Despite the emphasis in the literature on the more exotic erratics, chalk and flint are by far the most common stones in this till in West Norfolk. Many of the far-travelled erratics can be matched with rocks which crop out on the east coast of northern England and southern Scotland and it is clear that the bulk of the Hunstanton till was deposited by an ice-stream which flowed southward down the western side of the North Sea.

The relationship of the Chalky-Jurassic till to the Hunstanton till cannot be directly demonstrated at the present time. There have been records of reddish brown Hunstanton-type till overlying grey Chalky-Jurassic-type till, but these need to be interpreted with caution since the Hunstanton till is locally so rich in Cretaceous material as to be indistinguishable from the Cretaceous-rich parts of the Chalky-Jurassic till.

Hunstanton raised beach

At Hunstanton and Old Hunstanton the till overlies well-rounded chalk and flint gravels which appear to be a former beach deposit banked against an old cliff cut in Chalk, Red Chalk and Carstone. The feature made by this former cliff can be traced westwards from Old Hunstanton to Morston where Solomon (1932) described a similar beach deposit (the Morston Raised Beach) beneath supposed Hunstanton till.

In 1975 IGS made an excavation in the car park of the Le Strange

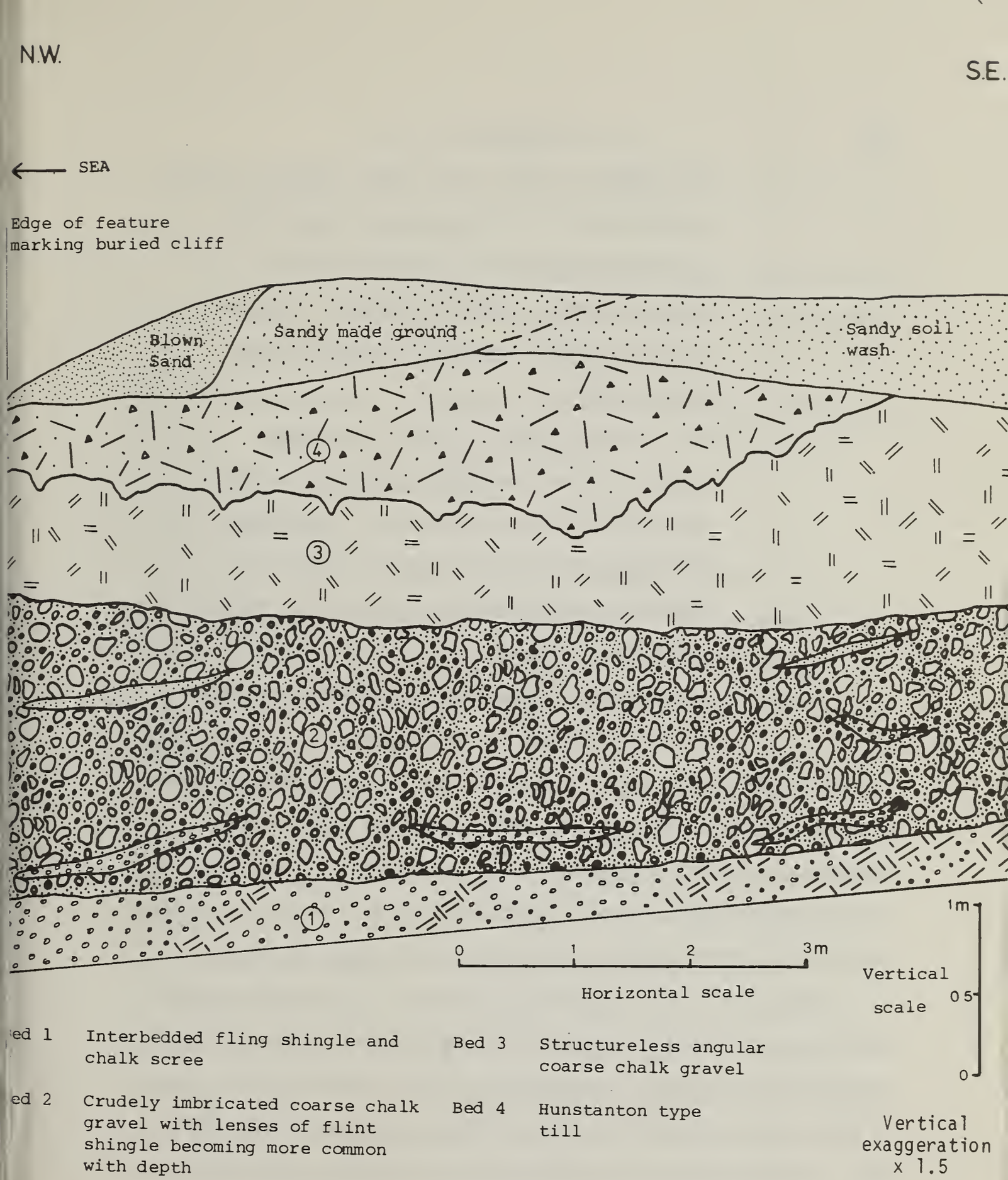
Arms Hotel, Old Hunstanton (TF 681425) on the edge of the former cliff to establish the stratigraphical sequence and, if possible, to obtain dateable shells from the Pleistocene beach. The following section was exposed (Fig. 3):

Blown sand; made ground and soil wash: blown sand banked up against seaward side of degraded artificial bank ..... up to 0.8m

Bed (4) Hunstanton till: stiff dull reddish brown sparsely stony clay; stones mostly fine gravel size flints and chalks with rarer Carstone, Red Chalk, rotted sandstone (?Carboniferous), granite, rotted coal, rotted ironstone, vein quartz and unidentified igneous rocks; irregular, cryoturbated base with pipes of till extending up to 0.3m into underlying bed ..... up to 0.9m

Bed (3) Cryoturbated chalk gravel: fine and medium gravel sized angular chalk fragments set in a matrix of chalk paste and dull reddish brown clay; larger chalk fragments joint bounded; thoroughly jumbled mass devoid of bedding or sorting; irregular passage at base into ..... up to 0.9m

Bed (2) Imbricated chalk gravel: sand grade to boulder sized angular, chalk fragments set in a matrix of poorly sorted sand and fine and medium gravel; larger blocks show imbricate structure dipping north westwards; lenses of fine sand in upper part of bed become replaced by thin interbeds of



ed 1 Interbedded fling shingle and chalk scree

ed 2 Crudely imbricated coarse chalk gravel with lenses of flint shingle becoming more common with depth

Bed 3 Structureless angular coarse chalk gravel

Bed 4 Hunstanton type till

Fig. 3 Trench section at Old Hunstanton showing relationship of Hunstanton type till to Hunstanton raised beach.

fine gravel in lower part; gravel composed of well rounded chalk and flint with rarer Red Chalk, Carstone, vein quartz, ironstone, jasper, Jurassic mudstone, coarse felspathic sandstone (? Carboniferous) and coal; irregular planar junction with ..... up to 1.8m

Bed (1) Shingle and chalk scree: clean, fine gravel composed of well rounded flints, chalk grains and rarer far-travelled erratics interbedded with beds of interlocking angular blocks of Lower Chalk which grade up into angular gravel sized chalk fragments set in a chalk paste; beds dip NW at about 5°; becoming predominantly gravel at seaward end of section ..... 0.3m seen

The lower part of the section, Beds (1) and (2), are similar in structure and content to parts of the debris cones which occur along Hunstanton cliffs at the present time. It seems likely that the excavation was made at a point where the old chalk cliff is indented and the Pleistocene beach is overlain by chalk scree and sludge.

Former exposures at Hunstanton gasworks (TF 672 402) showed the beach deposit to contain layers of shelly sand with a fauna of marine gastropods and bivalves interbedded with well-rounded gravels composed largely of far-travelled erratics (Whitaker and Jukes-Browne 1889, p. 90). The molluscan fauna, which can be matched with that of the present day Wash and North Sea, combined with the height of the gravels (maximum about 8 m above O.D.) suggests they were deposited under a climate and sea level similar to that of the present day. The problem

then arises of the origin of the glacially-transported erratics in the 'interglacial' beach (see below).

No outcrop of the Hunstanton raised beach has ever been described, since it appears to have everywhere been overridden by the Hunstanton till. However, there are extensive outcrops of gravels, similar to those of the Hunstanton raised beach and lying at a similar height above sea-level. These are the Tottenhill Gravels.

These are the Tottenhill Gravels.

Tottenhill Gravels

Between Hardwick (TF 631 182) and Wimbotsham (TF 608 058) an almost continuous narrow strip of flint gravel forms an eastern limit to the Fenland Holocene deposits. North of Hardwick, beneath the urban areas of Gaywood and South Wootton, patches of similar gravel have been exposed from time to time.

Whitaker *et al*. (1893, p. 91) interpreted this long strip of gravel as a terrace deposit marking the east bank of a forerunner of the River Gt Ouse. However, there is no evidence that the Gt Ouse, or indeed any other Fenland river, followed a course along the eastern edge of the Fens before its diversion there in Roman times and it is difficult to envisage a river without a western bank. Whitaker (*in* Whitaker and Jukes-Browne 1889, p. 92) later suggested that similar patches of gravel near King's Lynn might have a marine origin comparable with that of the Hunstanton raised beach. Few exposures have occurred in these gravels in recent years but those that have, at West Winch, Stowbridge and Tottenhill, have provided useful stratigraphical information.

A gas pipeline trench at West Winch (TF 631 167) revealed 3.0 m

of cross-bedded sand and well rounded flint gravel banked against a low cliff of Chalky-Jurassic till and soliflucted brown sandy till (Fig. 4). A section on the opposite side of the A10, a few metres to the west, showed 3.5 m of sandy, fine-grained, well rounded flint gravel with cross-bedding dipping gently eastwards. The notch at the base of the cliff was estimated to be about 4.0 m above O.D.

At Stowbridge (TF 614 074) about 3 m of similar flint gravel rests on Kimmeridge Clay. The upper surfaces of the gravels at West Winch (about 7.6 m above O.D.) and Stowbridge (about 6.7 m above O.D.) are at similar heights. The base of the gravels at West Winch (about 4.0m above O.D. estimated) and Stowbridge (about 3.7 m above O.D.) are also at similar levels.

The most informative section described in the Pleistocene rocks of West Norfolk in recent years has been that in Tottenhill Gravel Pit (TF 632 116) at the mouth of the Nar Valley. Here, the Nar Valley Beds can be seen to be unconformably overlain by a complex sequence of flint gravels (Fig. 5) which have been termed the Tottenhill Gravels (Gallois 1978). These gravels can be divided into two parts. The lower part, up to 5 m thick, consists of medium and coarse, poorly sorted, mostly angular gravels and is characterized by cross-bedding which dips steeply (20 to 25°) to the south-east and by frost wedge and cryoturbation structures. The gravels contain numerous pebbles of woody and reedy peat, soft brown clay, varved clay and Jurassic and Lower Cretaceous erratics, all presumed to have been derived from nearby outcrops of Nar Valley Beds and glacial deposits. The upper gravels (about 3.5 m thick) are fine and medium, are better sorted than the lower gravels and have planar cross bedding which dips west-

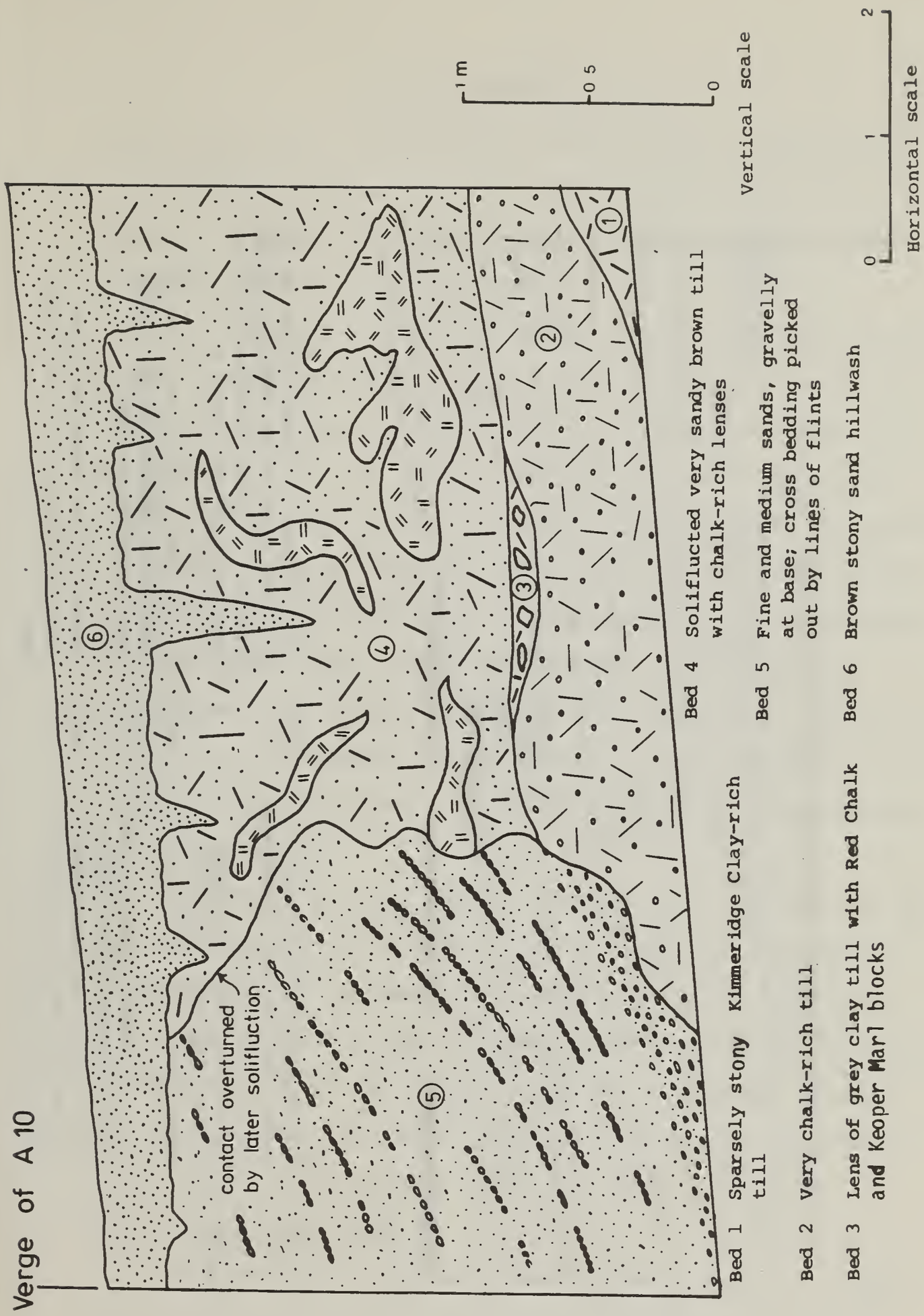
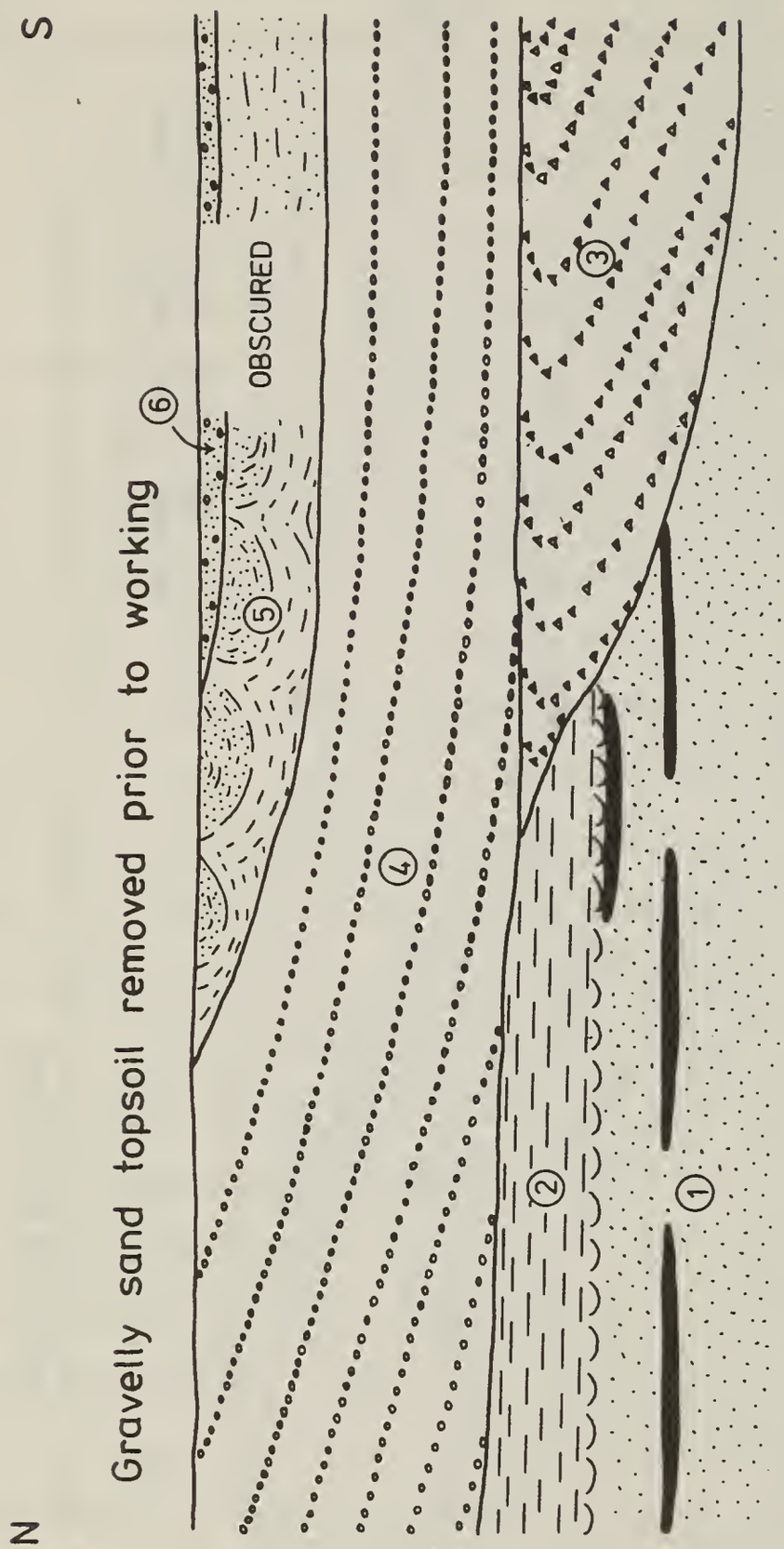


Fig. 4 Section exposed in No. 4 Gas Feeder Main trench, West Winch



Bed 1 Nar Valley Freshwater Beds: sands with lenses of wOOdy peat

Bed 2 Nar Valley Clay: dark grey marine clay with oyster-rich bed at base

Bed 3 Lower Tottenhill Gravel: poorly sorted, steeply cross-bedded flint gravel with much debris derived from Nar Valley Beds and Chalky-Jurassic till.

Bed 4 Upper Tottenhill Gravel: flint gravel with low angle cross bedding; patchy calcrete at base: transgressive across cryoturbation structures in 3

Bed 5 ? Till: cryotubated mixture of dull red-brown, sparsely stony, sandy clay and gravelly sand

Bed 6 Gravelly sand: cryotubated and irregularly piped into underlying bed

Not to scale: see text for thicknesses

Fig. 5 Diagrammatic section showing the sequence exposed at Tottenhill Gravel Pit

wards at 8° to 15°. The junction of the two units is a well defined, slightly uneven surface 5.0 to 5.2 m above O.D., in part calcite-cemented, along which the upper gravels truncate cryoturbation and bedding structures in the lower gravels.

In the south eastern part of the main pit (TF 6330 1135) the upper gravels are overlain by up to 1 metre of cryoturbated dull brown and reddish brown, sparsely stony, sandy clay and clayey sand which passes southwards along the section into dirty clayey sand. This lithology is reminiscent of the more sandy parts of the Hunstanton till, and although the stones are almost enitrely angular flints the clay and the underlying Upper Tottenhill Gravel also contain possible 'Bunter' quartzites and rare igneous rocks. These last include a distinctive quartz porphyry which was found in the reddish brown clay and is identical with material in the Hunstanton till at Hunstanton. The relationships of the Pleistocene deposits at the mouth of the Nar valley are shown diagrammatically in Fig. 6.

Baden-Powell and West (1960, p. 79) and Stevens (op. cit., p. 295) have described sections at Blackborough End gravel pits (TF 684 145) in which gravels of presumed glacial origin overlay the Nar Valley Beds. Whether these gravels represent the main mass of the Blackborough End Gravels, part of the Tottenhill Gravels or soliflucted material derived from the Blackborough End Gravels is unclear as the sections are no longer visible and were never satisfactorily described.

Correlation with Lincolnshire

Tills of similar lithology to both the Chalky-Jurassic till and the Hunstanton till occur in Lincolnshire and south east Yorkshire.

The Chalky-Jurassic till that infills the valleys beneath Fenland

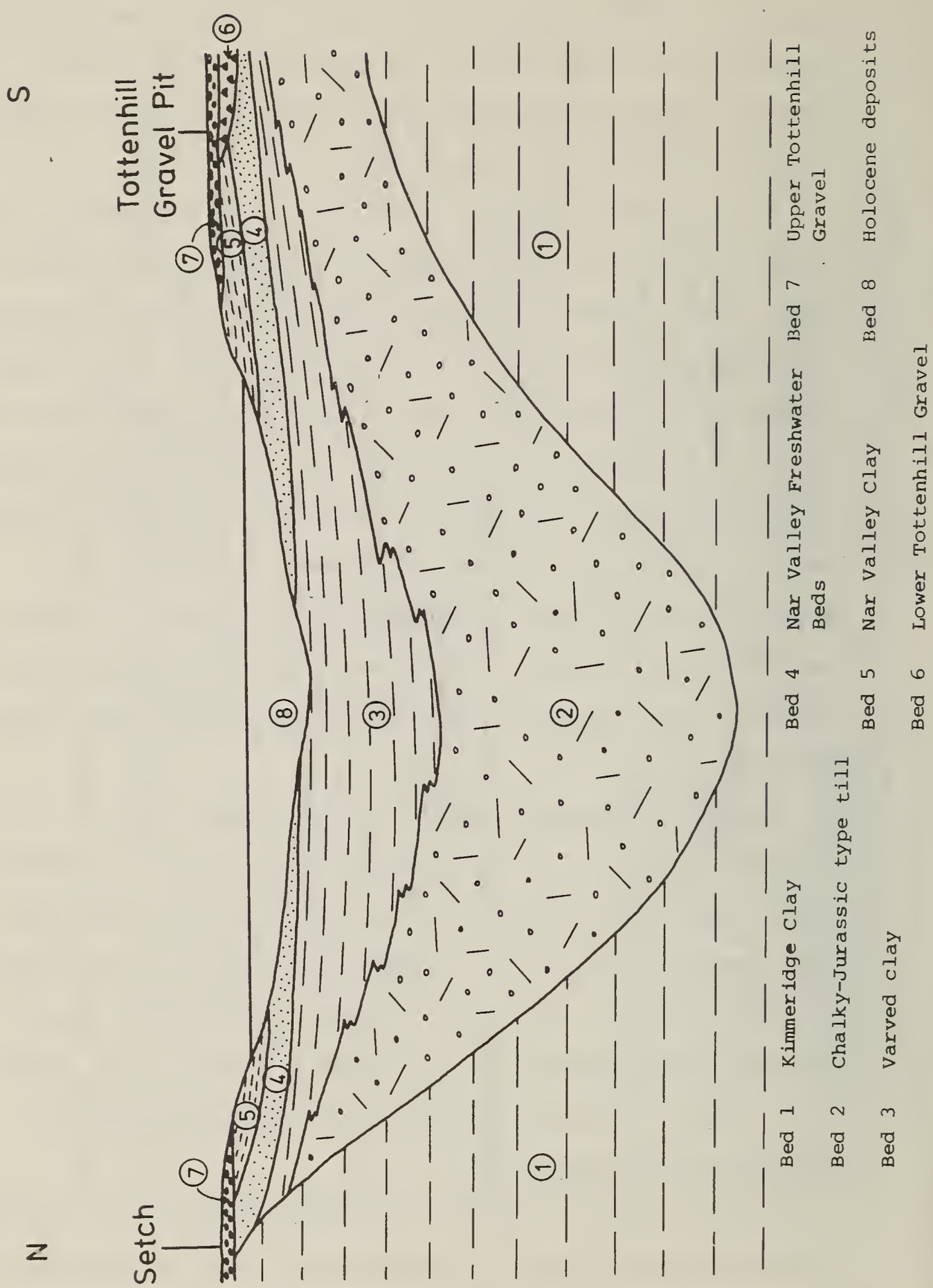


Fig. 6 Generalized section across the Nar valley at Setch

is lithologically similar to that which extensively outcrops in the Upper Jurassic clay vale of Lincolnshire. This latter is believed to be the oldest till in Lincolnshire and therefore seems likely to be the correlative of the Chalky-Jurassic till of West Norfolk. Much of the coastal plain of south east Yorkshire and east Lincolnshire is underlain by a complex of brown, reddish brown and purple tills which have been correlated with the Hunstanton till on the basis of lithology and landforms. The statement by Shotton et al.(1977, p. 274) that the thickest of the Yorkshire tills, the Drab, "has been traced via the Marsh Till of Lincolnshire into the Hunstanton Till of west Norfolk" is incorrect since the closest Lincolnshire and Norfolk outcrops are more than 30 km apart.

In the Holderness peninsula of Yorkshire Jukes-Browne (1885) described a series of tills (the Purple, Drab and Hessle), lithologically similar in part to the Hunstanton till, that overlie a beach deposit and chalk cliff comparable to that at Hunstanton. At Sewerby, Yorkshire (TA 199 686) Lamplugh (1888) described this beach as composed of shingle rich in far-travelled erratics (the same types as occur in the Hunstanton raised beach) together with a molluscan fauna (which can also be matched with that from Hunstanton) and vertebrate bones. The molluscan fauna is not diagnostic of age but it does suggest a similar climatic regime for both the Sewerby and Hunstanton beaches.

The vertebrates from Sewerby include warm climate forms of the elephant, hippopotamus and rhinoceros (Boylan 1967) and are said to be indicative of an interglacial rather than an interstadial phase (Catt and Penny 1966, p. 386). Catt and Penny (1966, p. 387) have also recorded an older till, the Basement Till, overlain by the raised

beach at Sewerby and it is from this latter till that the far-travelled erratics in the beach deposit are presumed to have been derived. If this interpretation is correct then, by analogy, one might expect to find an older till, lithologically similar to the Hunstanton till, in the offshore area close to the north Norfolk coast.

It has been noted above that the Chalky-Jurassic till appears to be restricted in Fenland and The Wash to the area lying to the south and west of the preglacial chalk escarpment. It is possible therefore that several phases of Hunstanton-lithology till were deposited to the north and east of the escarpment.

Organic freshwater silts at Dimlington, Lincolnshire (TA 391 217), which lie between the Basement and Drab tills, have been radiocarbon dated as about 18,500 years old (Penny et al. 1969). This date supports Straw's (1960) suggestion that the Hunstanton till represents the maximum extent of the last glaciation in East Anglia. This seems likely to be correct but it should be borne in mind that the correlation between the Drab and Hunstanton tills has yet to be conclusively demonstrated. The most convincing evidence for the correlation is circumstantial, the freshness of the Hunstanton till landforms (e.g. the Hunstanton Park esker) and the relationship of the till to the buried cliff and raised beach.

Correlation with southern Fenland

The distribution of the Chalky-Jurassic till and its associated sand and gravel deposits is patchy in southern Fenland but they appear to rest everywhere on solid rocks and to infill a preglacial valley system which is connected to that of West Norfolk. At March, Cambridgeshire the Chalky-Jurassic till is unconformably overlain by a

Pleistocene salt marsh deposit which in turn is overlain by shelly, storm beach gravels, the March Gravels (Gallois 1976, p. 18). These gravels have been tentatively correlated, on the basis of their height above sea-level and their fauna, with the Hunstanton raised beach. At a number of localities Marr and King (1928) and Baden-Powell (1934) recorded 'brickearth', a chocolate coloured stony sandy clay, overlying the March Gravels and thereby providing circumstantial evidence that the Hunstanton raised beach, Upper Tottenhill Gravel and March Gravels may formerly have been a single deposit overlain by the Hunstanton till, Tottenhill ?till and March 'brickearth' respectively.

The lower part of the Tottenhill Gravels, by virtue of their included frost structures and the torrential nature of their deposition, probably indicate a cold phase younger than the Nar Valley Clay. The relationship of these gravels to the gravels at Blackborough End and Wormeagay, both of which are presumed to be of glacial origin and associated with the Chalky-Jurassic till, is unknown. Gravels of this age have not been reported from southern Fenland.

All the rivers that drain into Fenland have flint gravel terrace deposits (usually designated Terrace 1 or Terrace 1-2) at levels close to or a little above O.D. In southern Fenland the rivers Cam, Lark, Gt Ouse, Little Ouse, and Wissey have extensive outcrops of this 'Fen edge gravel'. The field relationship of these gravels to the March Gravels shows the former to be the younger. Radiocarbon dates of organic material within the first terrace of the Gt Ouse at Earith have given an age of 42,000 years B.P. (Bell 1970). Frost structures within the gravels testify to cold conditions at times during their deposition. Their coarseness suggests deposition by torrents of meltwater since

these rivers are capable of carrying only clay grade material during the present temperate climate.

None of these gravel deposits extends more than a few kilometres seaward from the edge of Fenland: any downstream parts of the deposits therefore have either been completely removed by subsequent erosion (an unlikely explanation in the case of flint gravels such as these) or were never deposited. This suggests that the gravels were deposited as fans in a body of water such as a lake. If this latter explanation is correct then one would expect fine-grained lacustrine sediments to have been contemporaneously deposited over much of Fenland, but such deposits have not yet been found. Reconstructions of the limit of the glaciation that deposited the Hunstanton till (e.g. Suggate and West 1959) envisage the mouth of The Wash blocked by ice. A Fenland glacial lake would therefore be a likely consequence of this blockage and would explain the curious feature of the Fenland 'islands' such as Southery, Hilgay and March which appear to have been formed at some period before the deposition of the Holocene sediments which now surround them.

Summary of Pleistocene history

Finally, a word of caution. The main problems that occur in Pleistocene stratigraphy arise mainly from the laterally variable nature of glacial and interglacial sediments, from their lack of unique floras and faunas and from their potentially repetitive nature. This last point is of particular importance in West Norfolk and needs to be recognised if errors are not to be perpetuated and compounded. If ice moved across the area more than once, and if the direction of the ice movement was the same on each occasion, then one would expect tills of

similar lithology to be produced. There is evidence in West Norfolk for only one phase of deposition of Chalky-Jurassic till and one of Hunstanton till. However, these two tills are of different ages. It can be argued that when the Hunstanton till was being deposited at the most southerly extent of its ice-sheet, the area to the south, where the Chalky-Jurassic till crops out, experienced a periglacial climate. It is difficult however, to envisage a regime in which Chalky-Jurassic till was deposited in the south without an older Hunstanton-type till being deposited contemporaneously in the north. Our knowledge of these glacial events is still very limited.

Even more limited is our knowledge of the various Pleistocene temperate phases. The position of the Nar Valley Beds in the stratigraphical sequence seems secure but the record of other temperate phase deposits around Fenland, such as the Hunstanton raised beach, the Wretton interglacial deposits (Sparks and West 1970), the March Gravels and the salt marsh clay underlying them, and the Woodston Beds (Horton et al. 1972), is fragmentary. It is here that the difficulty of repetition of environment is likely to be most keenly felt for it is clear that sea-levels comparable to those of the present day probably existed on a number of occasions during the Pleistocene. Each maximum level is likely to have left behind patches of its more resistant deposits such as storm beaches and these may in some cases, as at March, have protected underlying less resistant strata. As yet we have no sure way of distinguishing the ages of these deposits. To make correlations on the basis of their heights above sea level merely assumes that they represent the deposits of a single temperate phase.

In the following summary of the Pleistocene history of West Norfolk

the simplest explanation has been devised that fits the field observations. This simple summary (Fig. 7) will undoubtedly become more complex as the stratigraphy of the area becomes better understood.

In preglacial times the rivers of West Norfolk drained westwards from the chalk escarpment to join a major river that ran northwards to breach the escarpment in the central part of what is now The Wash. These rivers became graded to a sea-level at about 100 m below O.D. prior to the onset of glaciation. The ice which deposited the Chalky-Jurassic till overrode this drainage system and the valleys became filled first with till and, in the late stages of the glaciation, with varved clay. Climatic amelioration then led to the deposition of freshwater gravelly sands and peats (the Nar Valley Freshwater Beds) which were overstepped by marine clays (the Nar Valley Clay) as sea-level continued to rise to at least 30 m above O.D. Analyses of peat and shells from the Nar Valley Beds have shown them to be beyond the range of radiocarbon dating (i.e.> 46,000 years B.P.).

There then followed a period of erosion of unknown duration during which large volumes of Chalky-Jurassic till and Nar Valley Beds must have been removed for the next deposit in West Norfolk consists of torrent-gravels containing frost structures (the Lower Tottenhill Gravel). In the absence of positive dating evidence the simplest assumption as to their age is that they were deposited during an early phase of the Hunstanton glaciation. No till of this age has been recognised in Fenland and it is possible that the area was inundated by a lake formed by ice blocking the mouth of The Wash.

The climate again became warmer and the Hunstanton raised beach and the Upper Tottenhill Gravel were deposited in a temperate period

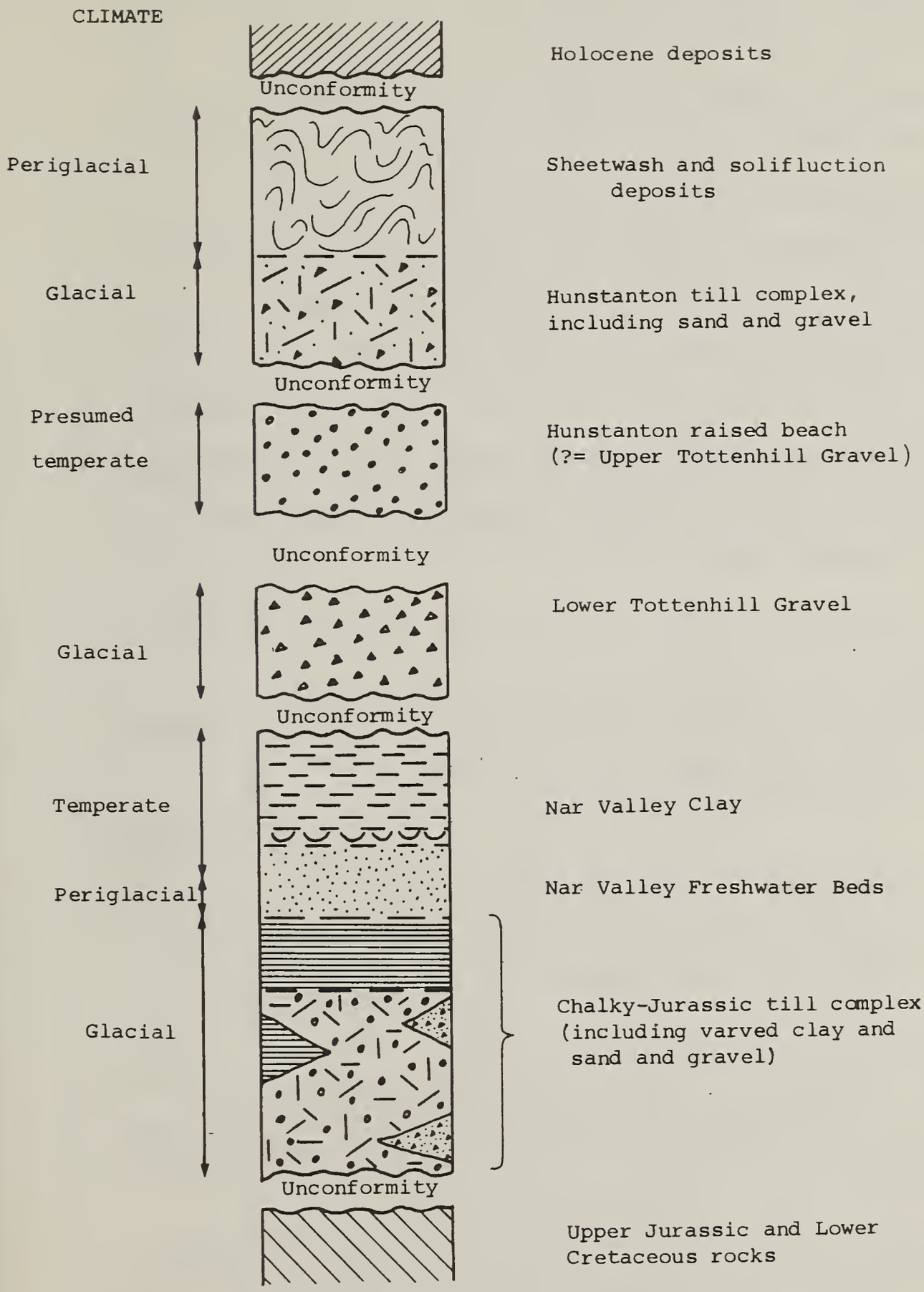


Fig. 7 Summary of the Pleistocene stratigraphy of West Norfolk

when sea-level was slightly higher than today. The last glaciation of West Norfolk was marked by the deposition of the Hunstanton till from ice that may have reached as far south as the Nar Valley at Tottenhill and southern Fenland at March. Finally, periglacial features such as frost polygons and stripes, stone polygons, 'hills and holes' topography, cambering and solifluction were extensively formed during this glaciation and after the last ice sheet had retreated.

The Pleistocene period came to end in West Norfolk when the sea re-invaded the low-lying parts of the area. Deposition of the Holocene deposits then began and the scene was set for the formation of the fascinating complex of sediments that was to become Fenland .... but that is another story.

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THE INFLUENCE OF CHALK FRACTURES UPON THE VALLEYS OF NORTH AND WEST NORFOLK

R. TOYNTON*

Introduction

The orientation of fractures within the Chalk of Norfolk have been measured at each of the outcrops located within the county. These outcrops are concentrated in the west of the county, near the northern coast and within the larger river valleys elsewhere. To the east of Norwich the Chalk becomes increasingly obscured by Crag deposits, the most easterly in situ exposure being at Postwick, about 6 km. to the east of the city. The western limit of the Chalk in Norfolk is shown on Figure 1.

Over much of central Norfolk the Chalk is covered by glacial deposits often exceeding 20 metres in thickness. These deposits, which consist in the main of boulder clays, tend to remove any influences of the underlying Chalk upon the present topography. Thus in seeking evidence for the influence of chalk fracture patterns on valley alignments, the five areas used as examples are all in the west and north of Norfolk.

The bedding of the Chalk dips towards the east at approximately 1°. The surface of the Chalk also declines in the same direction from maxima of over 80 metres above sea level in the west of the area considered, around Anmer, Great Massingham and Swaffham, to sea level a few kilometres to the east of Norwich. Further to the east the surface of

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the Chalk bevels down more steeply beneath the Crag and the Eocene deposits.

Valleys

Valley features in the Chalk may be divided into four types:-

1. Stream Valleys:

Surface valleys occupied by flowing water are the most common of those considered. Since these valleys are still undergoing modification by fluvial processes it is important to consider the general alignments of the stream valleys rather than the actual courses of the streams themselves. Even in areas with considerable thicknesses of glacial material most stream valleys are formed into the underlying Chalk.

The extreme headwaters of some of the streams flow in shallow depressions on the boulder clay surface and thus cannot be expected to display any particular orientational preferences.

2. Dry Valleys:

Numerous dry valleys occur in the western area of the Chalk outcrop, mostly where not overlain by boulder clay. Formed by fluvial processes at times when the water table has been at higher levels relative to the land surface, these features tend to be less sinuous than the valleys occupied by flowing water at present. Seasonal and longer term fluctuations in the level of the water table may cause some valleys to change from dry to wet on occasion.

3. Buried Valleys:

Though many present valleys may represent a postglacial re-excavation of preglacial features, it is more straightforward to define buried valleys as those preglacial forms which, due to infilling

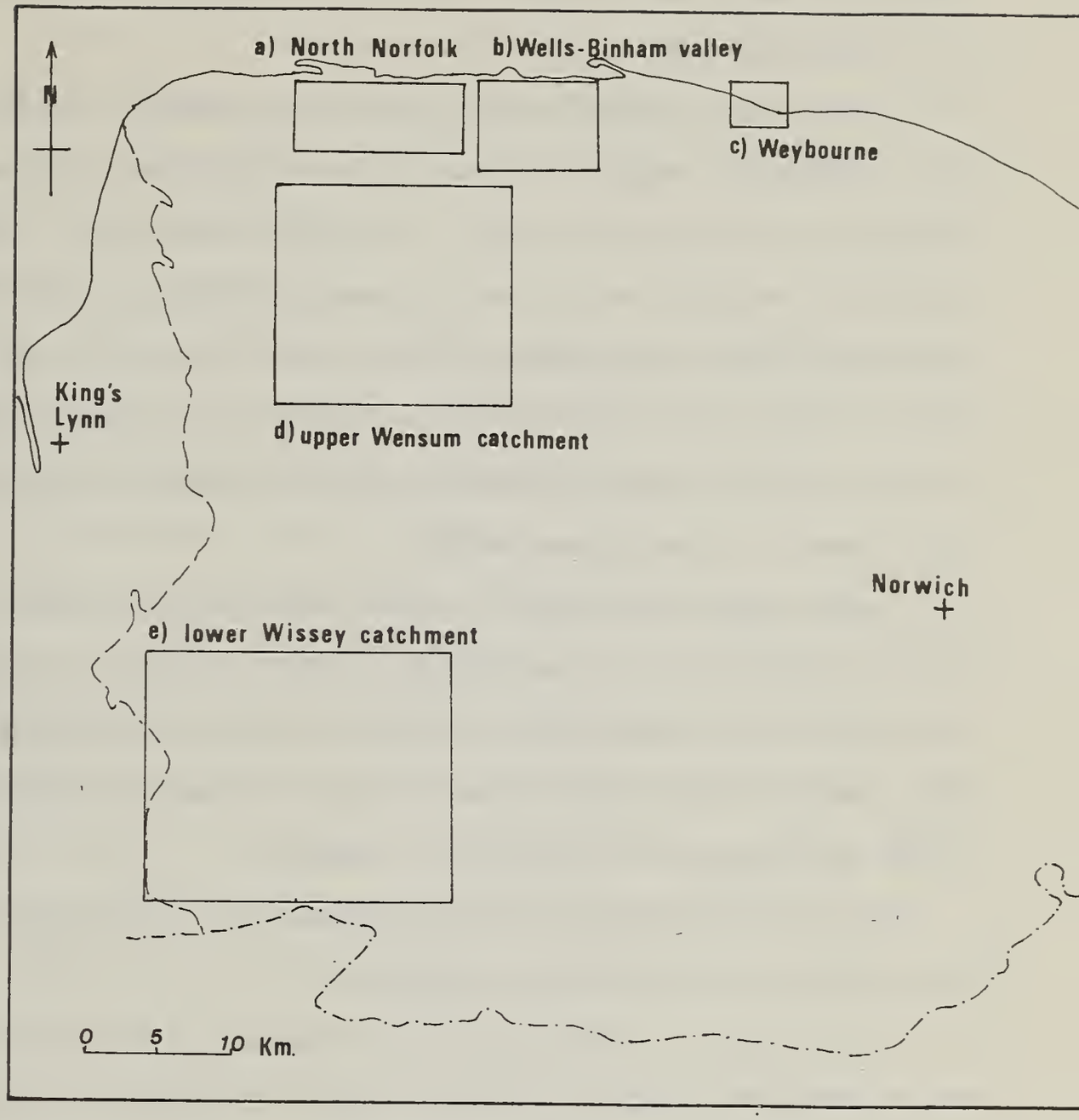


Figure 1. Location of example areas.

by glacial deposits, no longer have any expression on the land surface.

4. Buried Channels:

Known also as tunnel-valleys, the buried channels of Norfolk are deep, steep-sided features formed by water flowing under pressure beneath the Pleistocene ice sheet. The buried channels occur throughout most of Norfolk, and also occur commonly elsewhere in East Anglia (Woodland 1969). Near Hingham one such channel exceeds 100 metres in depth. Those in the south of Norfolk tend to be orientated from west to east, cutting across the watershed, whilst elsewhere they often occur beneath present stream valleys.

Being subglacially formed by water under variable pressure, the buried channels may vary considerably in depth from place to place. This lack of any semblance of a graded long profile distinguishes these channels from surface formed valleys. The buried valleys are infilled with glacial and fluvioglacial deposits.

The influence of Chalk fracture orientations upon valley features may involve the inheritance of alignments.

The preglacial valleys would have formed on a chalk surface and thus be directly influenced by that stratum. Similarly the buried channels would have been formed by water following lines of least resistance on the surface of the Chalk. In many cases these would be provided by the preglacial valley depressions in the Chalk surface; in others by the orientation of the dominant fracture set, the influence of which would be exaggerated by the mechanical weathering of the surface of the Chalk under periglacial and glacial conditions. Present surface valleys often follow the courses of buried channels possibly due either to the re-establishment of a preglacial drainage route imposed by the

general topography of the area, or to the preferential erosion of the less resistant infill material.

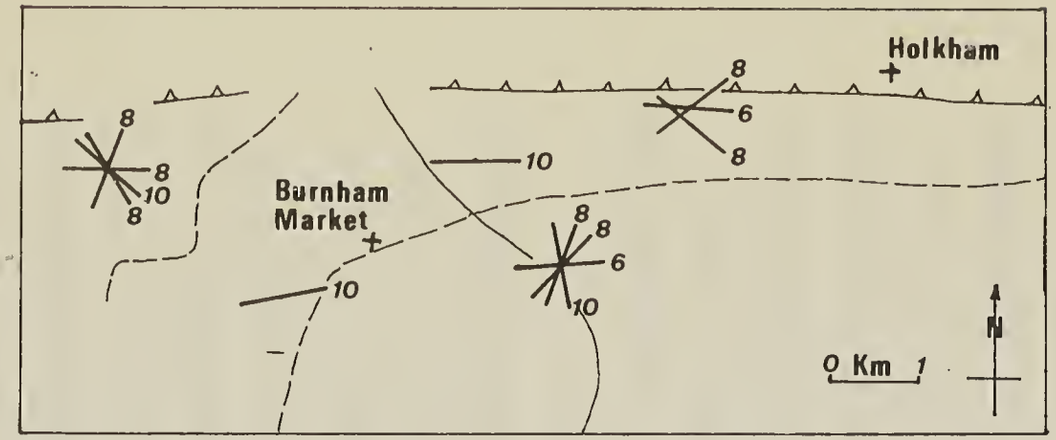
On Figures 2(a) to 2(e), where types are duplicated along a single alignment, only one feature has been included for the sake of simplicity. This has been done by giving present surface priority over buried features where they coincide.

Chalk Fracture Orientations

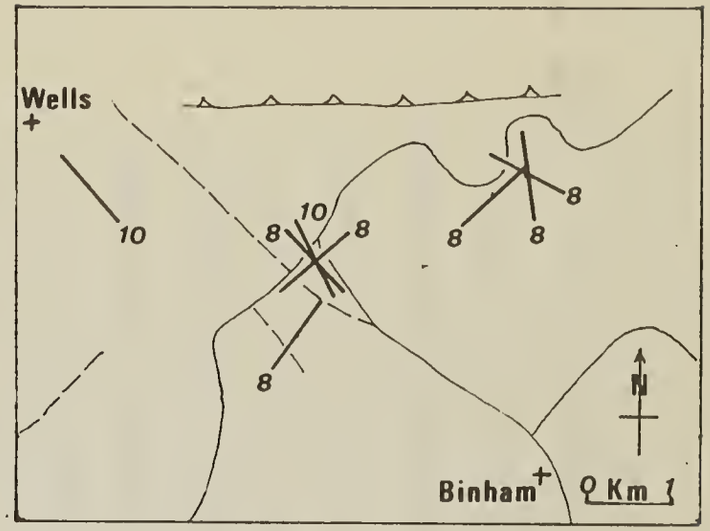
At every Chalk exposure of sufficient size located in Norfolk, fifty values of the strike and dip of fracture planes have been measured. These measurements have been taken at random points on the exposed face using a compass-clinometer.

Most of the exposures consist of vertical or near vertical faces of Chalk. In this situation it is likely that in addition to the pre-existing fracture sets, the pressure release due to the formation of the exposed face will form another fracture set parallel to this face. However, since most exposures have either more than one Chalk face or one which varies in orientation, by taking measurements at random points the pressure release effect is relegated to a background 'noise' above which the true fracture sets will show up.

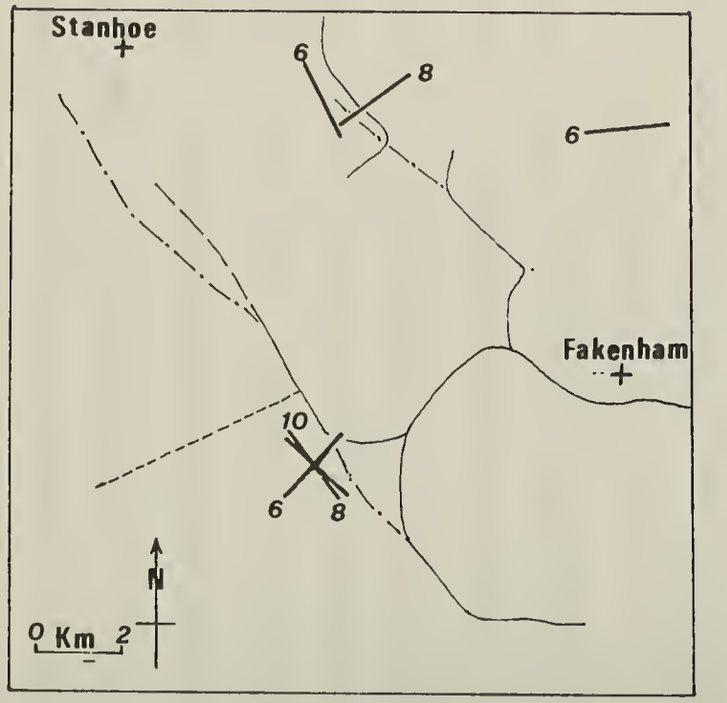
No measurements of width of fracture or of absolute frequency of occurrence have been made. Since all of the measurements have been taken from within the basal two metres of each exposure (i.e. the height easily reached while standing on the base), then depending on the height of each exposed section the level being measured will vary in its depth below the original Chalk surface. In most of the exposed sections it is very noticeable that the Chalk face becomes increasingly broken by fractures towards the top, and similarly that the width of



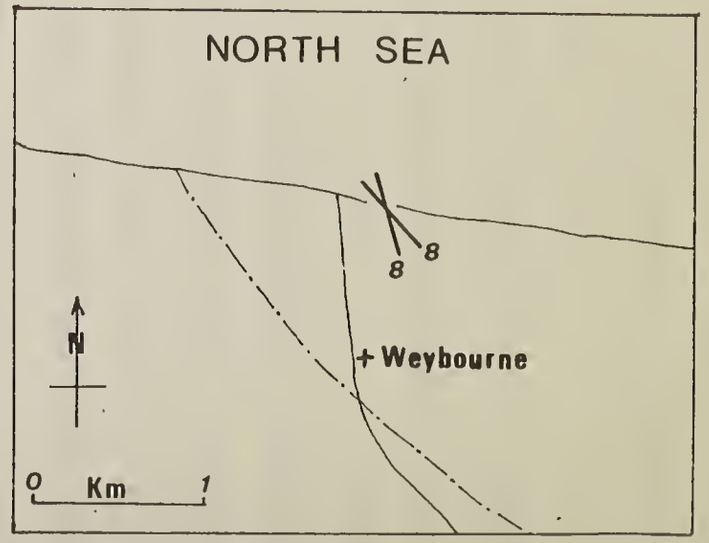
2(a) North Norfolk



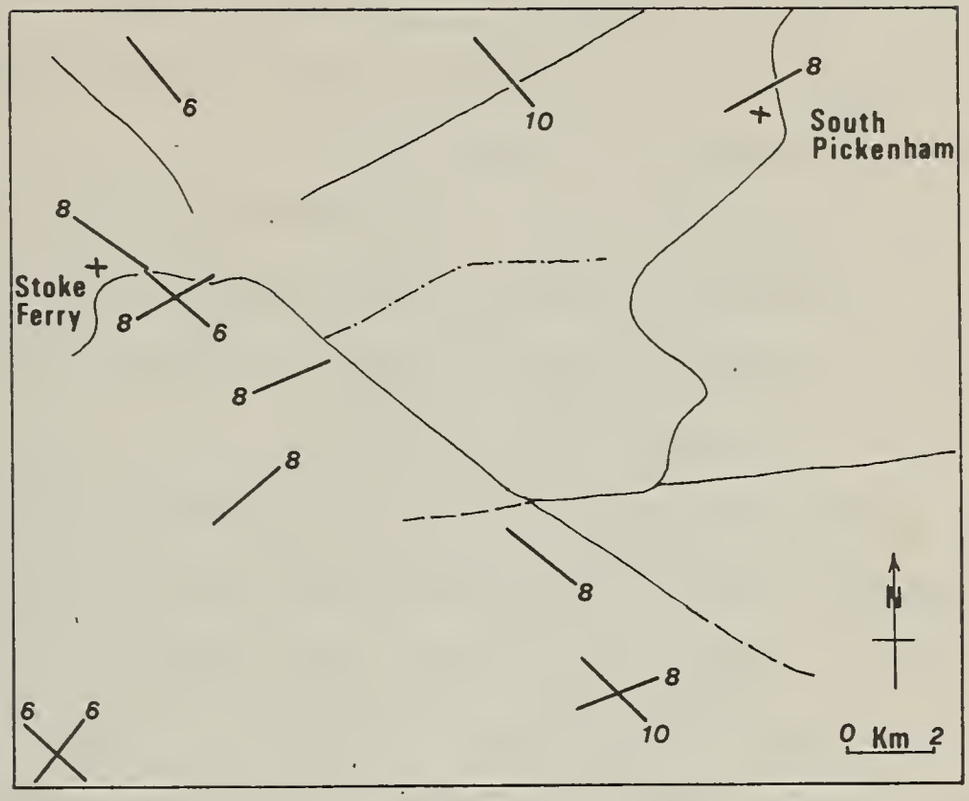
2(b) Wells - Binham valley



2(d) upper Wensum catchment



2(c) Weybourne



2(e) lower Wissey catchment

KEY TO FIGURES 1(a - e)

—— 8	Orientation of Chalk fractures with percentage concentration.
————————	Stream valley.
— — — — — —	Dry valley.
- - - - - - - - - -	Buried valley.
—·—·—·—·—	Buried channel.
△ △ △ △ △	Chalk slope.

the fractures may vary with depth, whether due to mode of formation or weathering processes. Thus, where the depth of the Chalk exposure below the original surface is not taken into consideration, measurements of the actual frequency and width of fractures are meaningless. The occurrence of certain orientations of fracturing within the fifty readings taken at each site is a measure in terms of relative frequency, and thus comparisons between sites are possible.

In order to determine the main orientations and relative strengths of fracturing, stereographic projections have been used. The use of the stereogram is a method of plotting planes on a circular net representing the surface of a sphere (Phillips 1971).

If the circular stereogram is viewed as one hemisphere, then a vertical plane intersecting this hemisphere appears as a straight line passing through the centre of the diagram. The orientation of this line from the north point represents the orientation of the vertical plane. Similarly a horizontal plane appears as a line around the circumference of the diagram. A plane with an intermediate dip thus appears as an arc, with the distance of the mid-point of the arc from the circumference of the stereogram as a measure of the dip from horizontal, and the points of intersection of the arc with the edges of the stereogram as the orientation of the strike of the plane.

The line normal to a plane (the pole) may be represented by a single point on the surface of the other hemisphere. Thus a point on circumference of the diagram is the pole to the vertical plane, the orientation of which is at 90° to the point. A pole falling at the centre of the diagram represents a horizontal plane, and so on.

Using this method the poles to the fracture planes measured at

each Chalk exposure have been plotted on separate stereograms. By considering the percentage of the poles which fall within each 1% of the area of the stereogram, concentrations of poles may be identified, contoured and compared.

Figure 3 shows two contrasting stereogram contour plots. That of measurements at Grimes Graves shows three distinct fracture sets. Two of these have dips which are on average near vertical, while the third, weaker set is in general horizontal. The orientations of the strikes of the near vertical fracture sets are marked outside the circumference of the stereogram with the additional number being that of the concentration in terms of percentage poles per 1% area.

The stereogram of the fracture poles at Marham shows in contrast no marked concentrations of near vertical fractures, the only distinct set being one dipping at about 10° to the north-west.

If a random set of dips and strikes were to be plotted on a stereogram the result should be a concentration of one over the total area. On the maps of Figures 2(a) to 2(e) only those orientations with concentration values of 8 or over are shown except where those of 6 are of special relevance to the regional pattern. On these maps, single lines at the relevant orientations are employed rather than the complete stereograms for the sake of simplicity.

Fracture Orientation and Valley Alignment

Figures 2(a) to 2(e) are largely self-explanatory, though a few additional notes may help draw attention to the important features.

a) North Norfolk

At each of the five Chalk exposures within this area a concentration of fracture orientations at about 090° exists. Over much of the

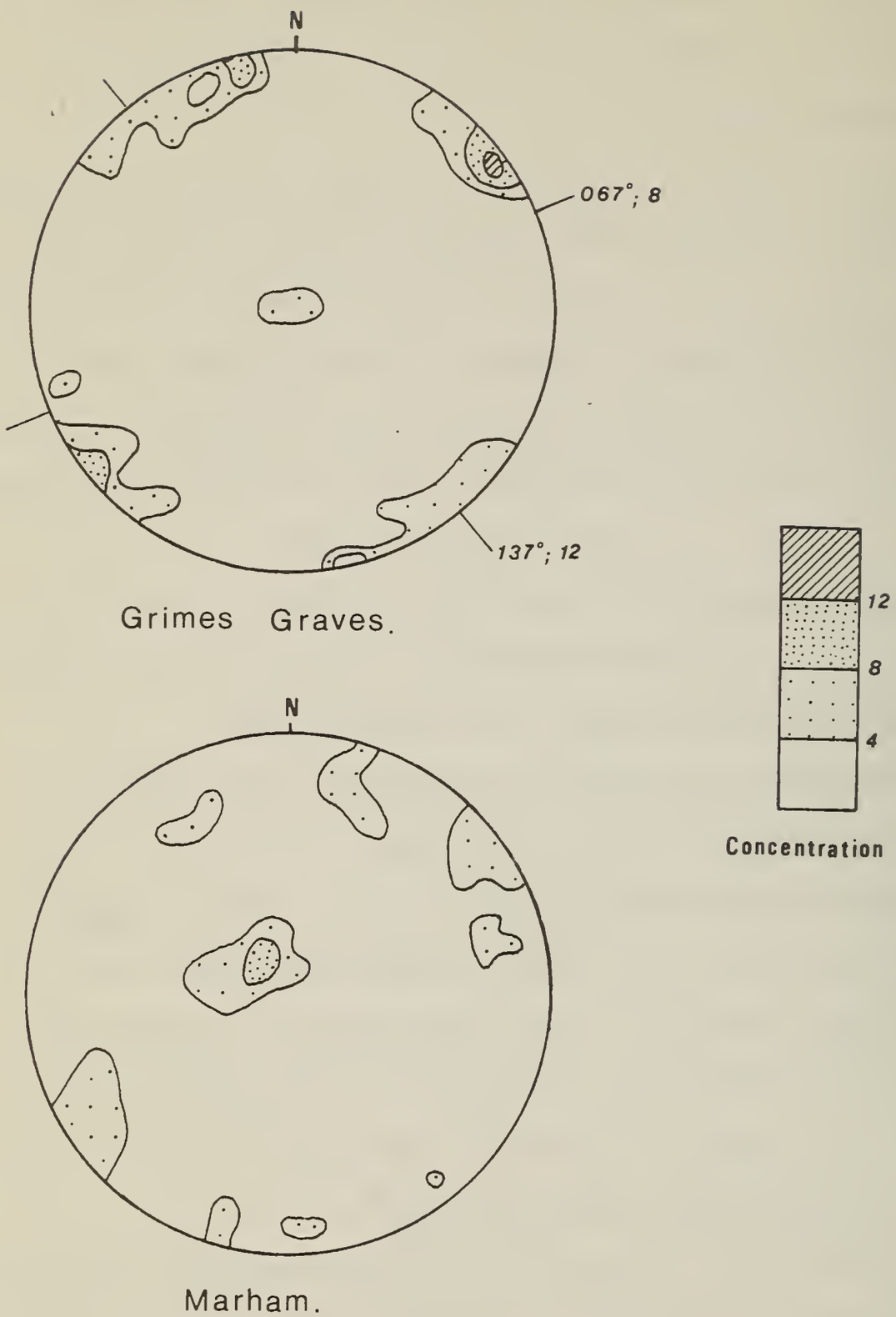


Figure 3. Typical stereograph plots of contoured poles to fracture planes.

rest of Norfolk orientations of around 050° to 060° and 130° to 140° are most common, and thus the north coast area is unusual. Noticeably close to the 090° orientation is the Chalk slope just inland from the coast, parallel to which is a shallow dry valley extending from Wells in the east to Burnham Overy in the west. A buried valley coincides with this dry valley. The east-west orientation of fractures in the Chalk close to the north coast of Norfolk may well be associated with faulting believed to exist with this same orientation in the basement rocks below the Chalk (P.N. Chroston, personal communication).

b) The Wells - Binham valley:

The valley of the tributary of the River Stiffkey which flows north-west from Binham is continued at a similar orientation north of the Stiffkey valley in the form of both a dry and a buried valley. The general line of the Stiffkey valley may also owe a debt to the fracture directions, but on a local scale this is not obvious.

c) Weybourne:

A buried channel at Weybourne, though varying in orientation through about 10°, is never more than 6° from one of the two main fracture orientations.

d) The upper Wensum catchment:

In this area two near parallel valleys are of interest. The westernmost of these is the valley occupied by the headwaters of the River Wensum in the south and by the River Tat in the central section. These rivers flow along the same valley line but in opposing directions. Northwards from the source of the River Tat the valley continues in its dry form, though the buried channel which underlies the rest of the surface valley occurs here further to the west, but still near

parallel. The buried channel linking the line of the River Tat to that of the upper Wensum continues beneath Helhoughton Common.

The second valley line is that of the upper River Burn with a buried channel linking it with a tributary stream valley of the River Wensum.

The orientations of both valley lines vary between 130° and 140°. The dominant fracture orientation at Helhoughton is 135°.

e) The lower Wissey catchment:

General fracture orientations of about 135° and 065° throughout the area are reflected in the lower stretch of the Wissey valley. This valley line, with a buried channel underlying much of it, extends southwards to West Toft Mere and possibly northwards as far as Barton Bendish. The northern extention is separated from the rest by the area of fen around Oxborough, across which no valley features can be traced.

The remarkably straight valley which runs north-east through Cockley Cley is very close in orientation to the Chalk fractures at four of the exposures in the area.

A further stretch of the River Wissey follows a valley line which extends both to Tottington in the east as a tributary stream valley and to Cranwich Heath in the west as a dry valley.

DISCUSSION

The five areas taken as examples suggest a similarity in orientations between Chalk fractures and valley alignments. This is summarised in Figure 4. The rose diagrams have been constructed by taking the maximum concentration values, where dips are over 45°, at 2° intervals of orientation on each of the stereogram plots, summing these

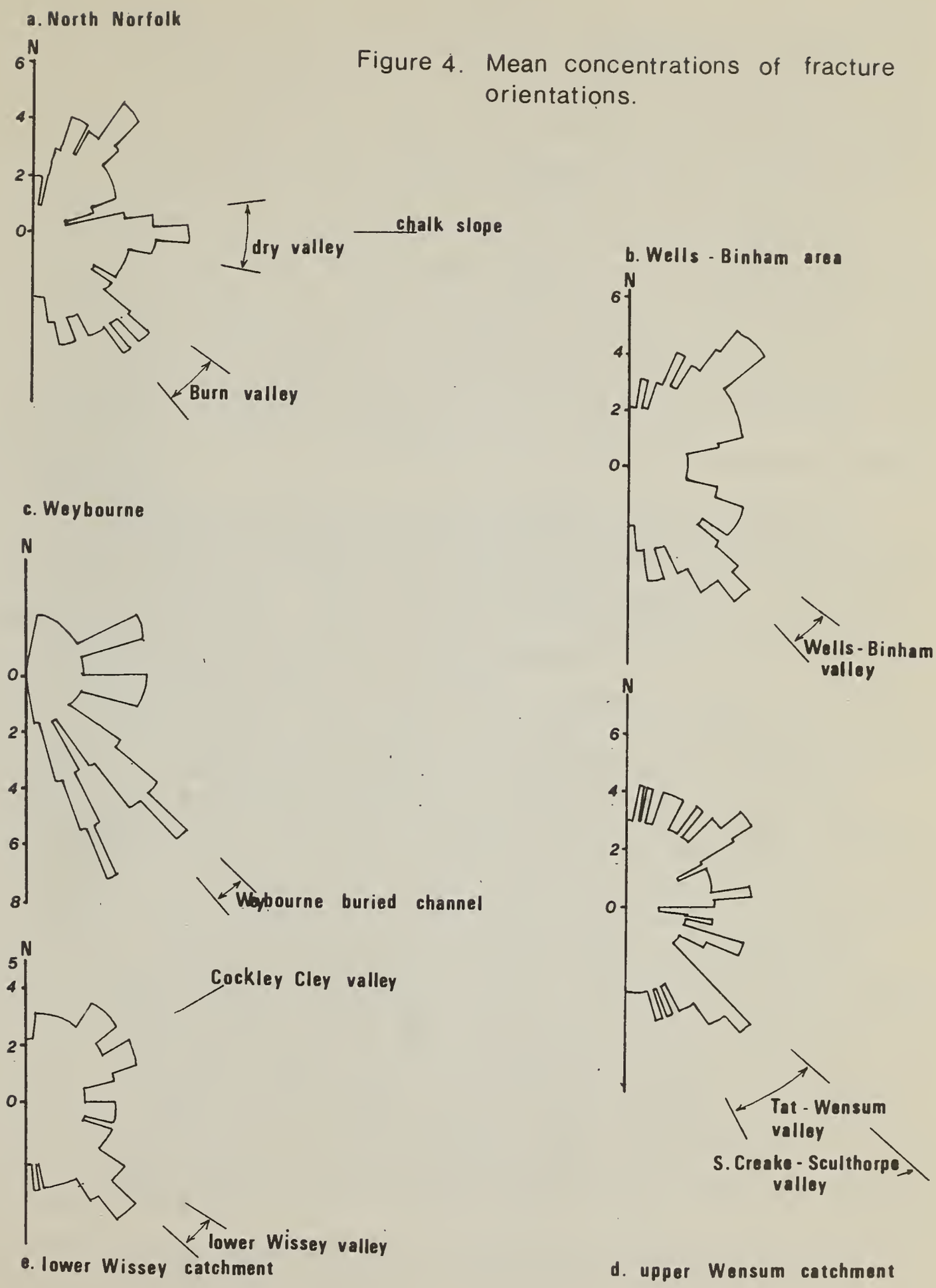


Figure 4. Mean concentrations of fracture orientations.

figures for all of the exposures within each area and then plotting the mean values thus obtained at 2° intervals. A single value or range of orientations of the main valley features are also shown, thus illustrating the close correspondence between valleys and fractures.

It is possible that the orientations of the fractures in the Chalk have been determined by the valley alignments, as a larger scale pressure release effect. Although in many cases the Chalk exposures are within the valleys and thus cause and effect are difficult to distinguish, the evidence does suggest that the fracture orientation is the controlling factor.

As has been previously mentioned, when all the Chalk exposures throughout Norfolk are taken into account, the dominant fracture orientations are from 050° to 060° and 130° to 140°. The valley features in four of the five example areas considered are largely in agreement with these orientations. Thus throughout the area there are common fracture orientations along which in places valleys occur.

If the valleys were responsible for fracture orientations, it could be expected that the valley-induced fracture sets would be superimposed upon a regional fracture set. This is not the case.

More specifically, taking the lower Wissey catchment as an example, there are instances, such as at Stoke Ferry and South Pickenham, where the fracture orientations coincide not with the valley alignments in the immediate vicinity, but at over 2 km. distance. Were the fractures valley-induced, surely their orientations would be expected to be those of the section of the valleys within which they occur.

Finally, the fracture orientations at Blackdyke Farm, shown at

the extreme south-west of the lower Wissey catchment area, coincide with those of the lower Wissey valley line which is more than 11 km. away at its nearest point. The Blackdyke Farm exposure is at the very western limit of the Chalk in Norfolk, is less than 10 metres above sea level, and yet is situated at the end of a low ridge rather than within a valley. Here, at the very "feather edge" of the Chalk mass and without the influence of any valleys, the fractures are still orientated in the same directions as in the lower Wissey valley, the upper Wensum valley and at Weybourne on the north coast.

Conclusion

In Norfolk there are numerous examples of relatively straight valley features which change in "role" along their length. The unspectacular nature of the topography makes these features obscure and thus they are best identified from maps.

Taking the Tat - upper Wensum valley line as an example, it would seem that the present streams, flowing as they do in opposite directions, may be responsible for creating the present surface expression of the valley, but that the two sections of stream valley are along a common alignment must be more than coincidence. It may well be that the course of the Tat buried channel has controlled the formation of the northern part of the valley, but since this channel does not extend as far south as the section occupied by the River Wensum, it would appear that the latter part has been influenced in its alignment by the same factor as that which originally controlled the alignment of the buried channel. The measurement of Chalk fractures taken at Helhoughton suggest that this common factor is the fracturing of the Chalk.

There is no suggestion that all of the valleys of west and north Norfolk are directly influenced by the fractures in the underlying Chalk. There does seem to be a weight of evidence however that this is the case in instances cited here.

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THE PLEISTOCENE SUCCESSION AT CORTON, SUFFOLK

W.K. POINTON*

Introduction

The importance of exposures in Quaternary sediments at Corton cliffs has long been established (Trimmer 1858, Gunn 1867, Blake 1890), and their regional significance is indicated by their designation as type site for the Corton Sands and Lowestoft Till (Baden-Powell and Reid-Moir 1942; Baden-Powell 1948, 1950) and the Anglian Glacial Stage (Mitchell et. al. 1973). Despite this importance, description of the sediments and stratigraphic relationships have hitherto been qualitative (Baden-Powell 1948, 1950; Blake 1890, Gunn 1867), restricted to particular stratigraphic units (Ranson 1968, West and Wilson 1968), or preliminary in approach (Banham 1971). This report gives the results of systematic study of sediments and sedimentary relationships at present exposed.

Corton is located at grid reference TM 545975, north of Lowestoft (Fig. 1a) in Suffolk. At this point the cliffs reach a height of approximately 25m O.D. Since 1969 the base of the cliff has been protected from marine erosion by a sea wall, resulting in stabilisation and colonisation by vegetation. Fresh exposures do occur, as a result of cliff failure, but this becomes progressively rarer as the basal material is not removed by coastal erosion.

Banham (1971) described a full succession of seven sedimentary units at Corton (Fig. 1b). At the time of the present study all units

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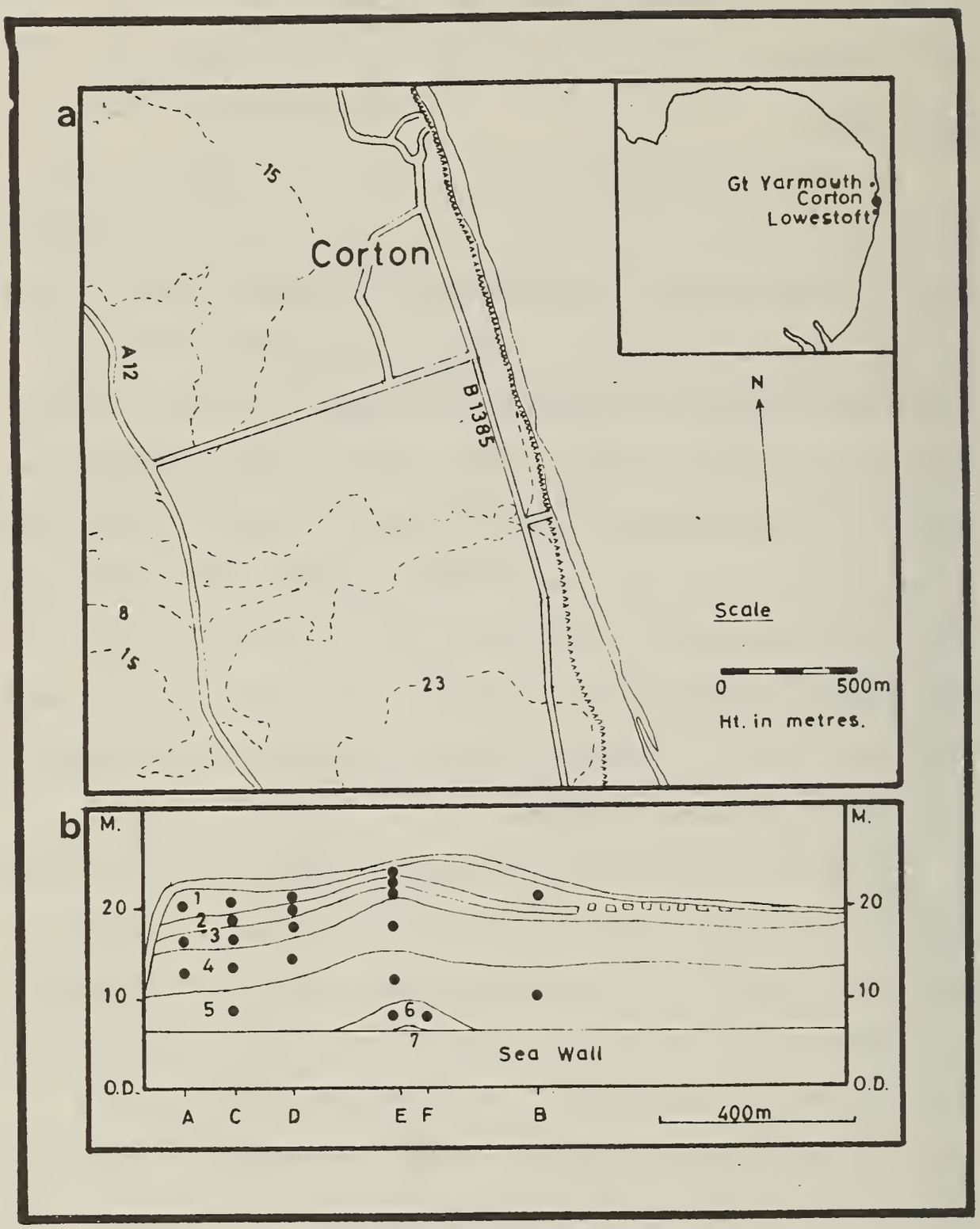


Fig. 1 Location and characteristics of Corton Cliffs.
a) The location of Corton.
b) Cross section of part of the cliff (After Banham 1971) A to F - site labels, black circles - deposits sampled at each site; 1 - Plateau Gravels, 2 - Pleasure Gardens Till, 3 - Oulton Beds, 4 - Lowestoft till, 5 - Corton Sands, 6 - Cromer till, 7 - Cromer Forest Bed Series.

were visible except the lowest, the "Cromer Forest Bed Series".

Procedure

Sedimentary structures and moist colour were studied in the field. The orientation and dip of elongate pebbles in each of the three tills were measured and the mesofabric characteristics were determined. Two dimensional preferred orientations are generalised as the resultant vector, and tested against randomness by the vector magnitude and Rayliegh significance test (Curray 1956). The orientation and dip of the "b" axis tabular pebbles in the Plateau Gravels was also measured, to determine the imbrication characteristics. These results were analysed visually.

Samples from all sedimentary units were taken back to the laboratory for further analysis. The particle size distributions were determined and the results are described in phi-units. Moment parameters were used to describe the particle size distributions of the Corton Sands and tentative comparisons made with the environmental diagnostic relationships described by Friedman (1961) and Koldijk (1968). The 4 - 16 mm sized stones from the tills were grouped according to lithologic type and the percentage frequency by weight was determined along with the percentage of calcium carbonate, in the fraction less than +3.75Ø (Dreimanis 1962). Carbonate content of the Oulton Beds was also determined.

Where possible, sample means and standard deviations have been computed and gross variability is shown by the coefficient of variation. For comparisons between the three tills the analysis of the variance is used. Unfortunately all sample populations are small and therefore the results are viewed with this inherent disadvantage in

mind.

The number of sample points studied at each site are recorded in Fig. 1b, and a summary of the results in Table 1.

Results

The Cromer Till

This deposit was the lowest unit exposed at the time of the field work. At its greatest exposure it was approximately 2.5 m thick and consisted of olive brown (2.5Y 4/4) poorly sorted, sandy till. The Cromer Till consists, on average, of 2.0% gravel, 58.2% silt and 17.2% clay (Table 1, Fig. 6), with a pronounced mode in the sand fraction.

The 4 - 16 mm size fraction consists largely of flint (61.4%) with some quartz (12.6%), hard chalk (7.2%), Jurassic and Lower Cretaceous rocks (14.1%) and metamorphic rocks (4.7%). Many of the stones such as the flint, which has a deep patina, show evidence of previous weathering. Many of the pebbles are sub-rounded. Soft chalk is absent and suggests that local chalk outcrops in central Norfolk do not contribute to the deposit. This is supported by calcium carbonate content of less than 12%.

Only one sample point for fabric analysis was studied (Fig. 2a). A resultant vector of 106° - 286° with a vector magnitude of 48% (significant at the 99% level) was determined. This direction is consistent with other results (West and Donner 1956). Folding within the till shows folds overturned predominantly towards the S.S.W. which Banham (1975) suggests indicates ice movement from the N.N.E. The fabric maximum could be a transverse peak of the type described by Banham (1966).

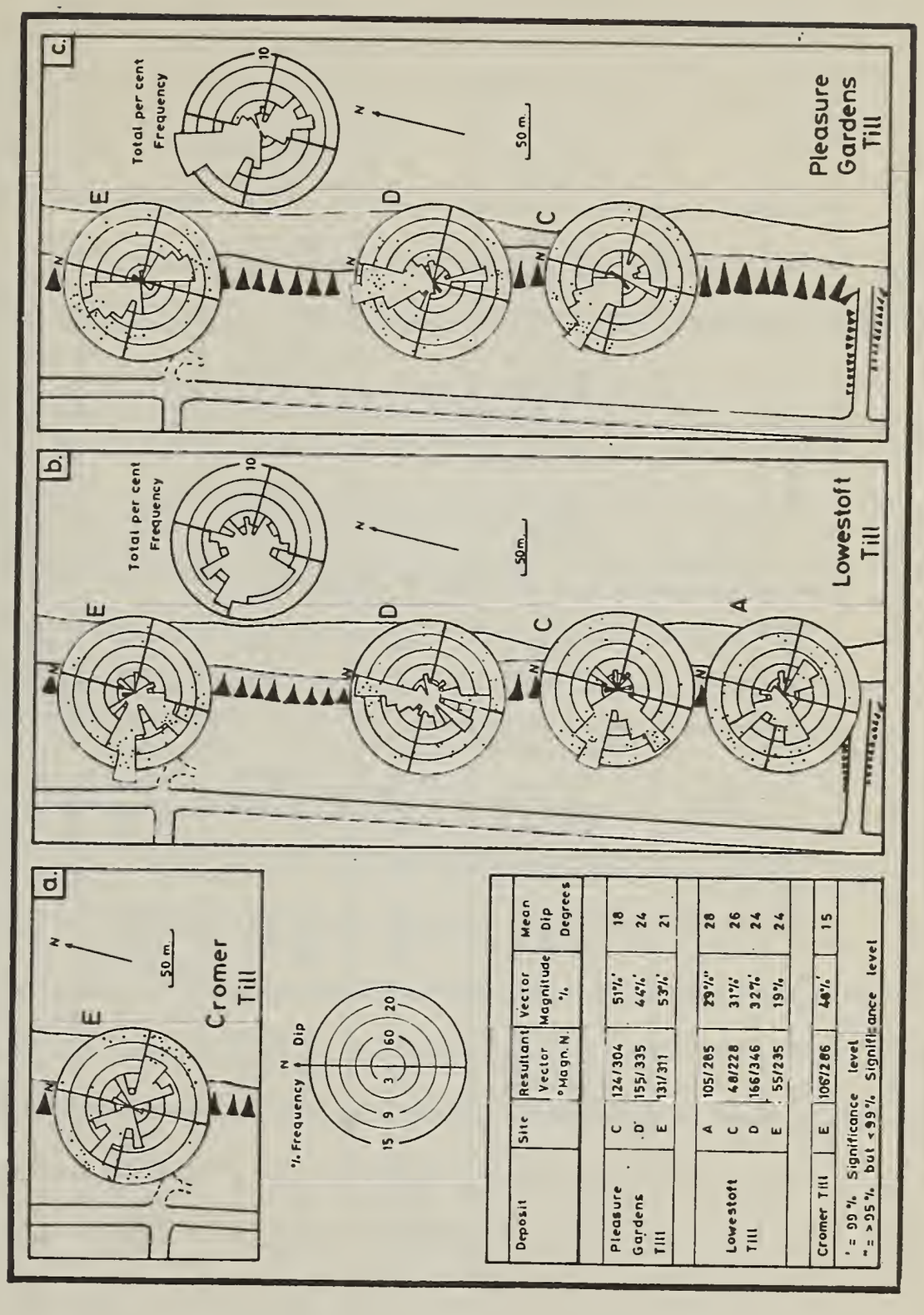


Fig. 2 Results of fabric analyses of the three tills exposed at Corton.

TABLE 1. Sedimentary Properties of Deposits Exposed at Corton Suffolk

Sediment	Colour	$CaCO_3$	Particle Size Distribution				Stone Content 8 - 16 mm					
			% Clay	% Silt	% Sand	% Gravel	% C	% F	% J.C.	% I	% M	% Q
Plateau Gravels (Range of means)			0.0 0.0	0.4 0.5	98.8 30.4	0.8 69.1						
Pleasure Gardens Till (Mean) (S.E.) (Vc)	N3-N8	69.0 11.1 28.0	27.0 8.9 57.0	52.1 6.7 22.0	19.2 3.8 35.0	1.7 0.6 65.0	63.2 13.9 38.0	26.0 13.3 89.0	8.8 2.7 53.0	0.0 - -	0.0 - -	3.0 1.4 80.0
Oulton Beds (Mean)	N4- 2.5YR4/3	32.0	19.9	58.3	21.8	0.0						
Lowestoft Till (Mean) (S.E.) (Vc)	N2-N3	40.0 3.2 14.0	42.7 2.3 9.0	41.2 1.8 8.0	11.2 0.6 9.0	4.9 1.0 37.0	69.2 3.3 8.0	11.3 3.0 45.0	17.8 3.6 35.0	0.7 - -	0.0 - -	1.0 0.45 80.0
Corton Beds (Range of means)	2-5Y 7/3 10YR 6/6		0.0 35.8	1.9 40.6	97.5 23.6	0.6 0.0						
Cromer Till (Mean)	2.5Y 4/4	12.0	17.2	22.1	58.2	2.0	7.2	61.4	14.1	0.0	4.7	12.6

Key: C = Chalk, F = Flint, J.C. = Lower Cretaceous and Jurassic, I = Igneous, M = Metamorphic Q = Quartz and Quartzite

The folding indicates that the ice which deposited the till moved into the area from the N.N.E., off the North Sea. The absence of fresh chalk, and the pronounced mode in the sand fraction of the till, which indicates the closeness of the source, are further evidence of ice movement in this direction.

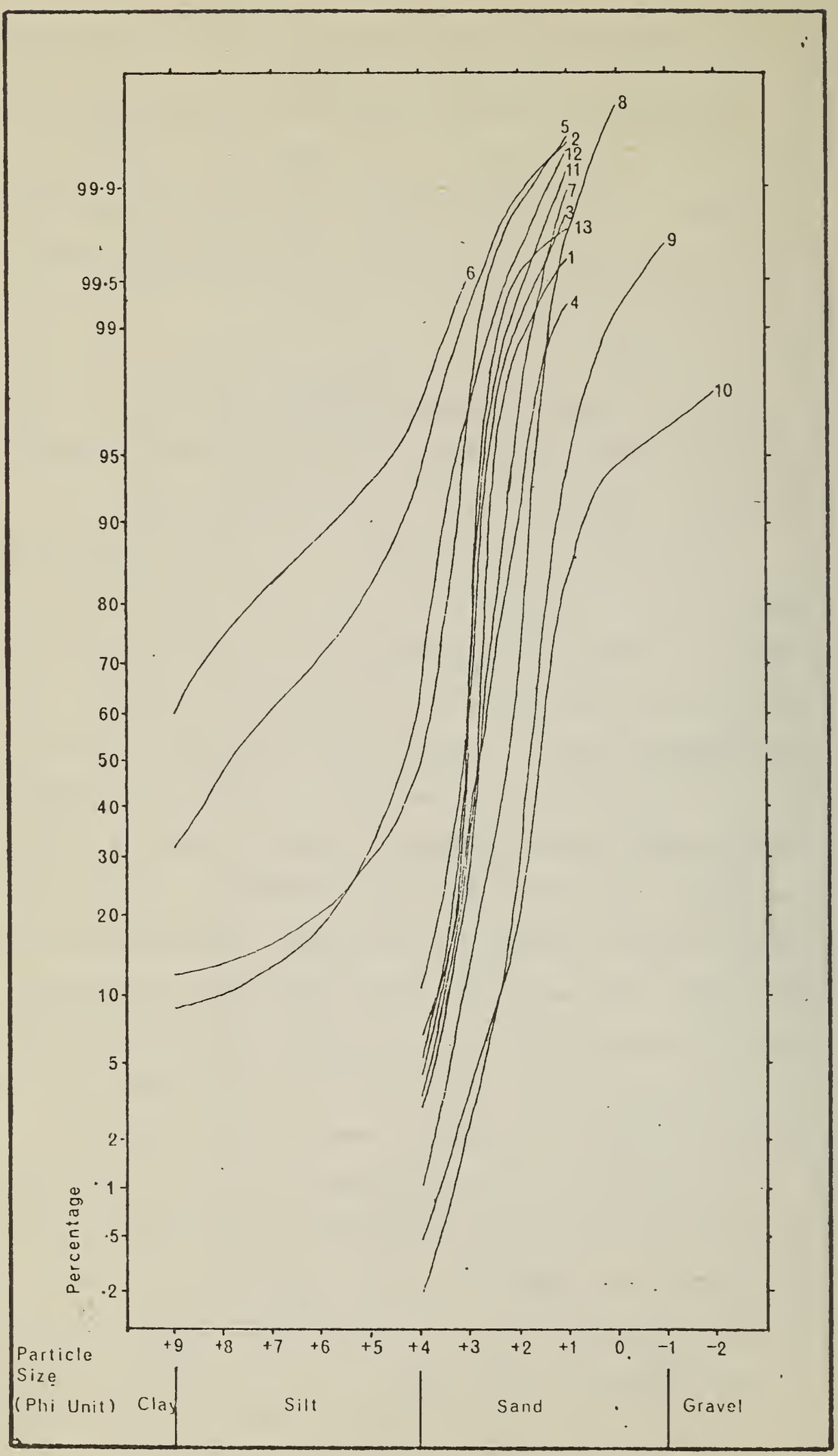
The Corton Sands

The Corton Sands are exposed along the entire length of the cliffs and are composed of sandy gravels, fine sands, and silts ranging in colour from light yellow (2.5Y 7/3) to orange (10YR 6/6).

The particle size distributions (Fig. 3) indicate well sorted sands and silts. Moment parameters derived for comparison with the results of Friedman (1961) and Koldijk (1968) were not conclusive but may possibly indicate deposition in a fluvial environment. In places thin laminated clays, 1-2 cm thick, were found within the silts.

The sands and silts are well bedded with some ripple bedding in the fine sands and dune bedding in the coarser sands, at the base of section E. Dips of 25° and 26° with orientations of 211° and 119° respectively indicate water flowing from an approximate north westerly direction. Silts were observed intruding into the overlying fine sands and Lowestoft Till intruded into the underlying sands (Fig. 4), these structures appear, therefore, to reflect secondary settlement, related to instability caused by inverted density gradients.

Ice wedge casts have been recorded in the Corton sands at Corton and at Burgh Castle (Ranson 1968) indicating deposition in a permafrost environment (Pewe 1966). This is supported by the full or late glacial plant remains found in the clay lens at exposures south of Lowestoft (West and Wilson 1968).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+5
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+3
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+1
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−1
−2
Particle Size (Phi Unit)
Clay
Silt
Sand
Gravel

Fig. 3a

Fig. 3b

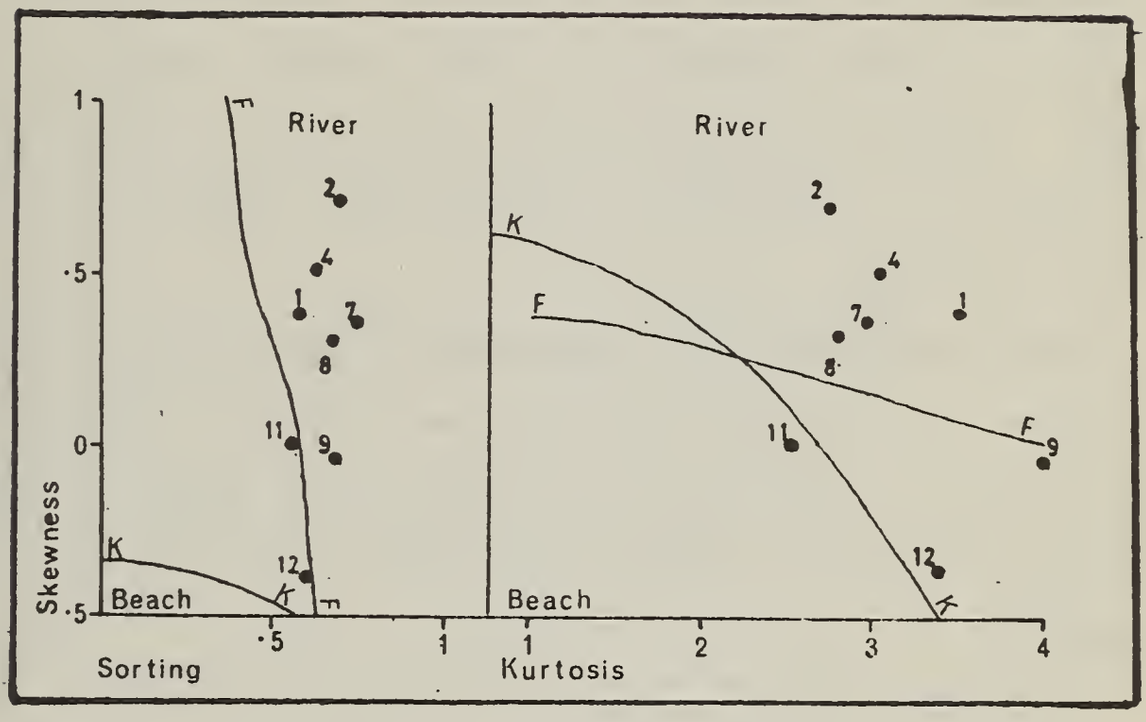


Fig. 3 Particle size distributions (a) and environment sensitive parameters (b) for the Corton Sands.
F - F, - Friedman (1962). K - K, - Koldijk (1968)
C, E & B - the sites from which samples were taken.

The occurrence of the foraminifer Jadammina macrescens and Eleocharis parvula, in the clay lens studied by West and Wilson (1968) indicate brackish conditions. The former, found at the base of the lens, also suggests the possibility that the lower sands are partly marine in origin (West and Wilson 1968).

The association of the fauna, secondary structures, assemblage of sediments and environment sensitive parameters suggest that the Corton Sands may have been deposited in a fluvial, possibly estuarine, environment. Sedimentation occurred during a cold period after wastage of the Cromer Till ice but prior to transgression by Lowestoft Till ice.

The Lowestoft Till

The Lowestoft Till comprises a poorly sorted, stiff, dark grey (N3) clay. At all sites its thickness was greater than 2 m, but it was difficult to obtain more accurate measurements because of slumping which also limited the choice of sample sites to the top 2 m of the deposit.

The deposit contains on average 4.9% gravel (Vc = 37%), 11.2% sand (Vc = 9%), 41.2% silt (Vc = 8%) and 42.7% clay (Vc = 9%), (Table 1, Fig. 6).

The 4 - 16 mm size fraction is variable and consists of chalk 69.2% (Vc = 8.0%), flint 11.3% (Vc = 45.0%), Lower Cretaceous and Jurassic 17.8% (Vc = 35.0%) and quartz 1% (Vc = 80%). A carbonate content of 40% suggests that much of the finer fraction is composed of comminuted chalk of which the most likely source is central and west Norfolk.

The till fabric results for all samples show orientations which differ from random at a level greater than 95% (Fig. 2b). The mean

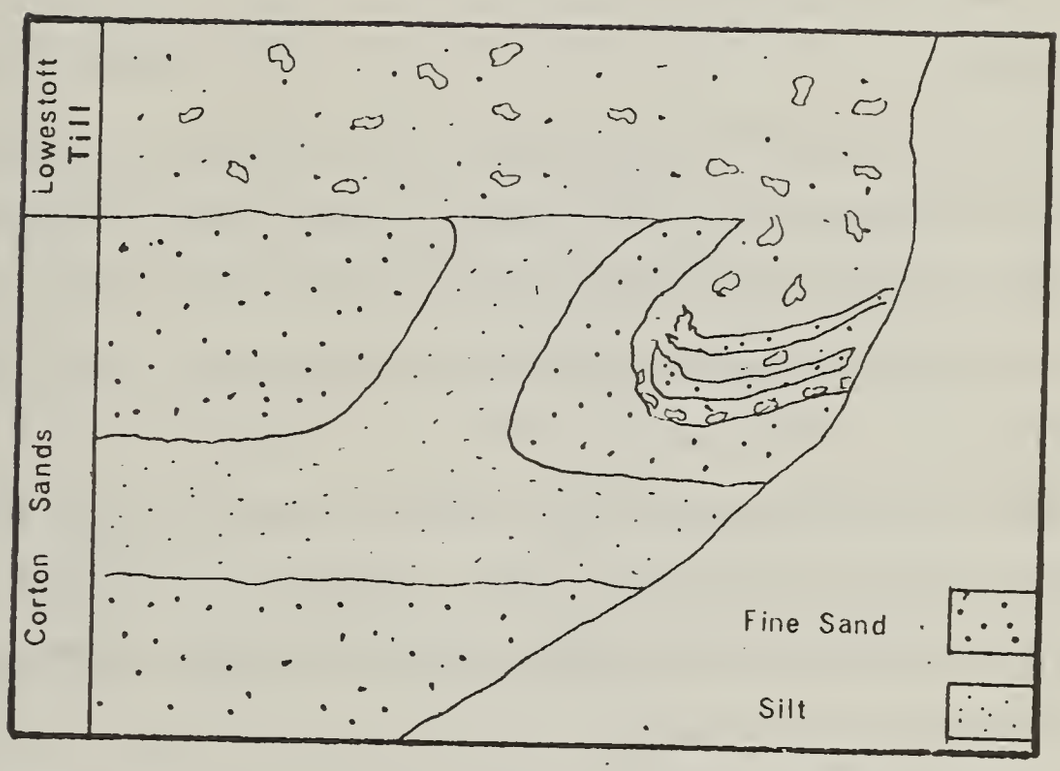


Fig. 4 Load deformation structures in the Corton Sands.

strength of the resultant vectors is 27.8% (Vc = 21%) and the mean dip 26.5^{o} (Vc = 7%). Individual vector strengths are distributed systematically from the bottom to the top of the section, with stronger values at the base. Orientation trends range from 48°/228° to 166°/346° and along with mean dip values are apparently randomly distributed. This reflects the absence of a regional energy source (Rose 1974) and may suggest that depositional characteristics were influenced by local conditions.

Results obtained for the Lowestoft Till at Corton show similarities to those recorded by Perrin, Davis and Fysh (1973), for the Lowestoft till in Suffolk, particularly with respect to the high clay and calcium carbonate contents (49.8% and 43% respectively in Perrin et. al. 1973).

The stone content and calcium carbonate content suggest that the material, of which the Lowestoft till is composed, was derived from a westerly direction. The mesofabric properties suggest that deposition was influenced by local factors, such as those associated with melt-out processes associated with the later stages of glacial decay.

The Oulton Beds

These lie immediately above the Lowestoft Till and consist of grey (N/4) to greyish yellow (2.5 YR 4/3), clayey silts, overlain by sandy silts and fine sands. They indicate relatively still water deposition with occasional current flow.

Mean calcium carbonate content of 32% suggests deposition from a source rich in calcium carbonate such as the Lowestoft Till. Alternatively this could be due to a high faunal activity but there is no evidence to support this (Banham 1971).

The particle size properties, colour, calcium carbonate content and stratigraphic relationship to the Lowestoft Till suggest that the Oulton Beds consist of slow flowing or still water sediments derived from the Lowestoft Till. The gradual change from clay to silt and fine sand suggest a shallowing sequence, probably associated with a proglacial lake such as are found at the present day in Spitzbergen (Boulton 1968).

The Pleasure Gardens Till

The till is of variable thickness (observed range .9 m to 2.5 m) with definite chalky banding displayed at all sites. Colours ranges from greyish white (N/7-N/8) within the chalky bands, to dark grey (N/3lN/4).

The Pleasure Gardens Till is poorly sorted (Table 1 Fig. 5), with an average of 1.7% gravel (Vc = 65%), 19.2% sand (Vc = 35%), 52.1% silt (Vc = 22%) and clay 27% (Vc = 57%). The high silt and clay content again suggest that Mesozoic clays form the predominant source material.

The lithology of the 4 - 16 mm size fraction is characteristically variable and composed largely of chalk 63.2% (Vc = 38.0%), and flint 26% (Vc = 89.0%), with the remainder made up of Cretaceous and Jurassic rocks.

All samples are rich in calcium carbonate (mean 69%) but there is considerable variation (Vc = 28.0%) between samples. Examination of the carbonate content and chalk percentage of the gravel fraction indicates a tentative relationship between the two. The sample with the highest percentage of chalk (84%) had the lowest carbonate content (47%) in the matrix. Similarly, with the other samples, as the chalk

gravel decreased the carbonate content of the matrix increased, suggesting the possibility of some comminution of the chalk during subsequent reworking of the deposit.

The strong mesofabric properties and evidence of comminution of the chalk gravel, indicate deposition by dynamic processes. The mechanical composition suggests a glacial origin for the sediments. These properties, plus observed chalky banding in the Pleasure Gardens Till, have been associated with the development of flow tills in Spitzbergen (Boulton 1968).

The very high local rock content is consistent with what might be expected if the material is brought to the surface of the glacier by englacial shearing at the snout (Boulton 1968). Subsequent melting, would generate high pore water pressures causing instability (Boulton 1968) resulting in flow.

The Plateau Gravels

Immediately above the Pleasure Gardens Till are the Plateau Gravels which consist largely of medium gravels, with fine to medium sands. The modes in the gravels occur in the 8 mm to 16 mm range and the 0.5 mm to 1 mm range indicating possible bedload and saltation components in a fluvial system, or transitional, lag deposits, between the surf and swash zones on a beach (Visher 1969).

The deposit is strongly imbricated (Fig. 4) but with a variety of modal directions. Such properties might suggest either a braided or meandering channel.

The Plateau Gravels appear to have been formed by a shifting and variable fluvial process, such as that associated with a high, but fluctuating, discharge and a plentiful sediment supply. Such

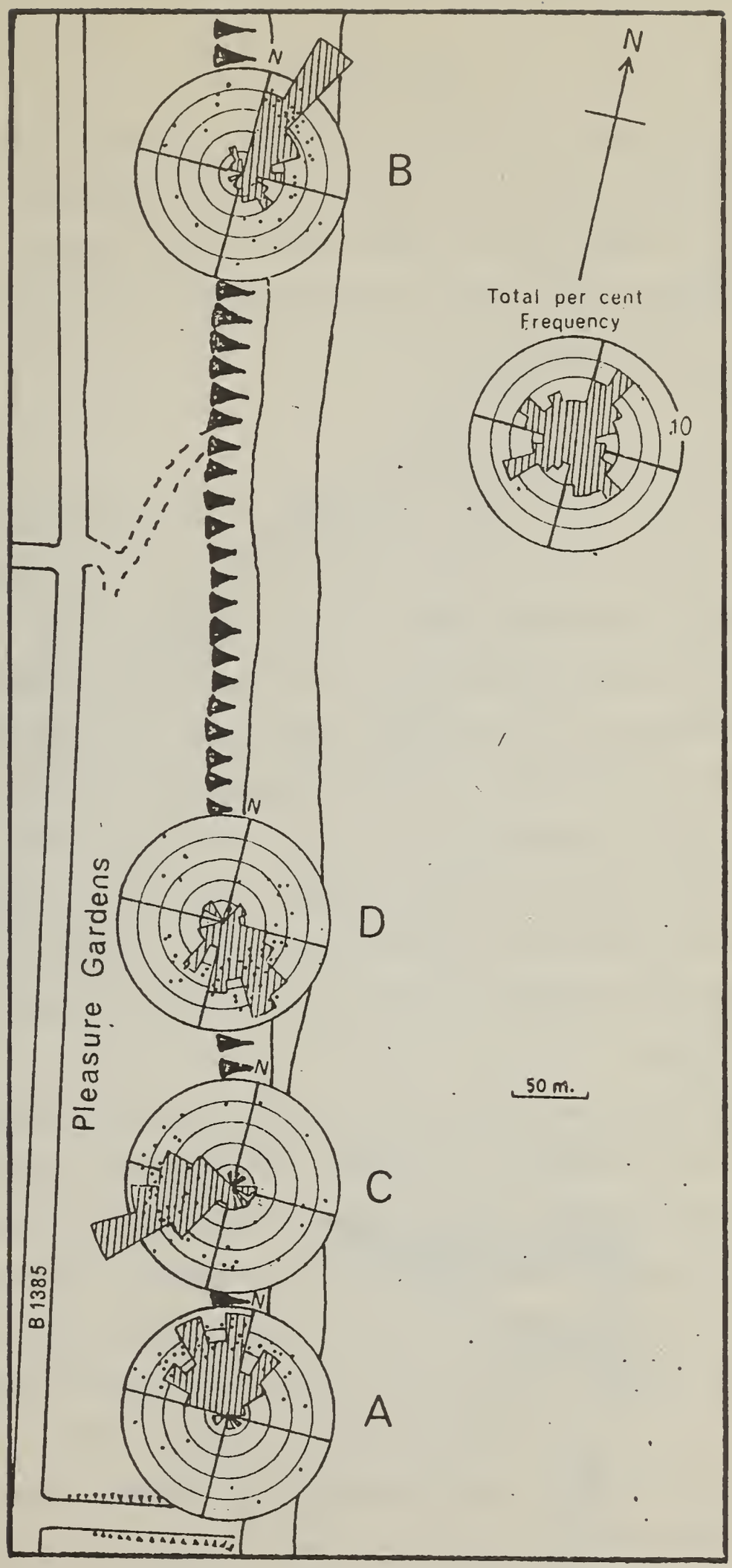


Fig. 5 Fabric analysis results for the Plateau Gravels.

(Key as in Fig. 2).

conditions are typical of a braided rather than a meandering fluvial system (Allen 1970, Leopold and Wolman 1957). The stratigraphic relationship to the lower deposits suggest that they were formed by meltwater streams, highly charged with glacially derived sediments, in front of a melting glacier margin.

Discussion

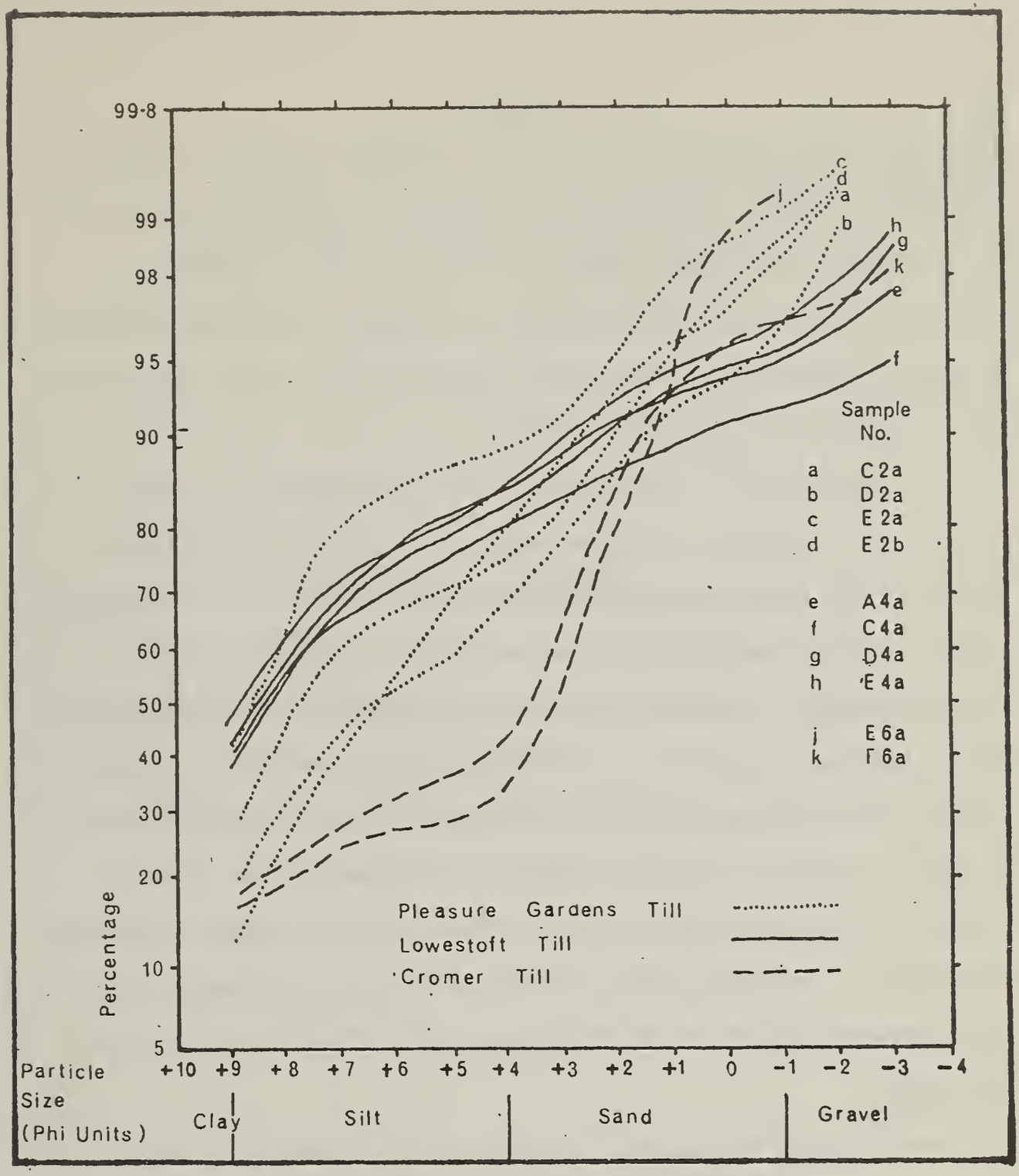
a) Comparisons of the three tills

The three till units differ with respect to calcium carbonate contents. The Cromer till is deficient in $CaCO_3$, whilst the content of the Lowestoft and Pleasure Gardens Till is high to very high.

The particle size distributions (Fig. 6) show that the Lowestoft and Pleasure Gardens Tills are similar in most respects, except that the latter is more variable. Possible differences in the gravel fractions, and $CaCO_3$ content, of the two tills, are most probably accounted for by comminution of the chalk gravel during the prevailing depositional conditions of the Pleasure Gardens Till. Both tills are different from the Cromer Till, particularly with respect to sand silt and clay fractions.

The lithological compositions of the gravel fraction of the three tills shows large differences in the chalk, flint and quartz contents, between the Cromer and the other two tills. In contrast differences between the Lowestoft and Pleasure Garden Tills are small. This suggests a similar provenance for the Lowestoft and Pleasure Gardens Till but a distinct difference in provenance between these and the Cromer Till.

The evidence suggests that the Lowestoft and Pleasure Gardens Tills are probably related to the same glacier, derived from the west,



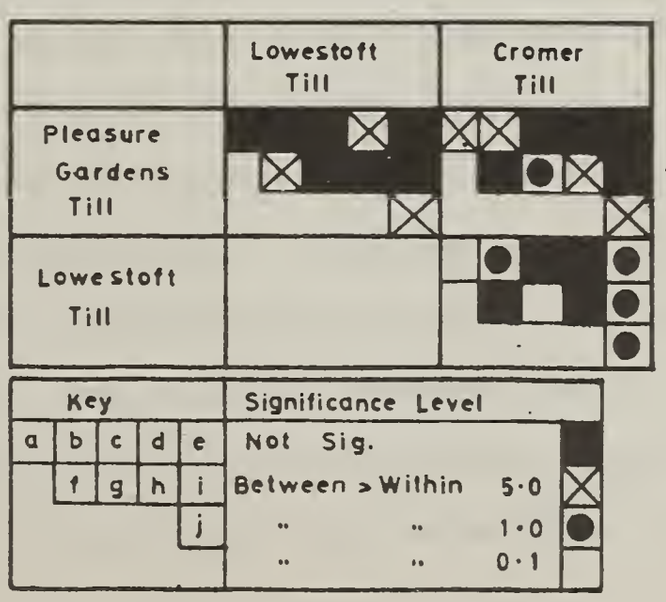


Fig. 6 Particle size distributions of the three tills at Corton and the results of an analysis of the variance test. a - chalk, b - flint, c - Cretaceous, d - Jurassic, e - quartz, f - gravel, g - sand, h - silt, i - clay, j - $CaCO_3$.

and the differences that do occur are related to the mode of deposition (Banham 1971). The Cromer Till, however, is different from both the Lowestoft and Pleasure Gardens Tills with respect to $CaCO_3$ content, sand, silt, and clay contents and the major lithological groups, suggesting deposition from a source unrelated to the other two tills.

b) The age of the deposits

The Lowestoft Till, Oulton Beds, Pleasure Gardens Till and Plateau Gravels represent a possible sequence of glacial, pro-glacial, flow-till and outwash deposition without any evidence of a significant hiatus. As the Lowestoft till can be dated as Anglian by relation to biostratigraphic interglacial deposits elsewhere in East Anglia, this age is applied to the whole of the depositional sequence. Since the Cromer Till was deposited before the Lowestoft till sequence and can be seen at Corton to lie above deposits of Cromerian Age, it must therefore also be ascribed to the Anglian. It would appear therefore that there is evidence of the two separate glacial episodes both of which occurred during the Anglian Stage of the Middle Pleistocene.

Conclusion

The evidence from Corton suggests therefore that the Cromer Till was deposited by ice which moved into the area from the E.N.E. The development of the Corton Sands indicate that the glacier retreated and was replaced by a fluvial possibly estuarine environment in which sands, silts, and clays were deposited. Ice-wedge casts (Ranson 1968) and cold environment flora and fauna (West and Wilson 1968) indicate that a periglacial climate persisted throughout their deposition.

In turn the area was then overrun by the glacier that deposited the Lowestoft Till. This glacier moved across the area from a west-

Table II The Corton Stratigraphy presently exposed and the suggested division into sub-stages (After Mitchel et al 1973)

	Deposit	Sub-stage	Stage
6.	Plateau Gravels	Lowestoft	Anglian
5.	Pleasure Gardens Till		
4.	Oulton Beds		
3.	Lowestoft Till		
2.	Corton Beds	Corton	
1.	Cromer Till	Gunton	

erly direction having passed over and entrained the Jurassic and Cretaceous sediments to the west. The upper part of the till unit analysed at Corton appears to have been deposited during the later stages of this episode, when melting was the predominant process. Retreat of the ice margin appears to have been followed by proglacial lake development and sedimentation in which the Oulton Beds accumulated. These lake sediments were in turn buried beneath flow till units derived from the same ice sheet until mud flow deposition was replaced by outwash sedimentation and the Plateau gravels were aggraded.

The sequence currently exposed at Corton can be grouped into three sub stages for which the following names (Table II) Lowestoft, Corton, and Gunton, have been suggested (Mitchell et. al. 1973).

Acknowledgements

The author thanks his wife, Susan, for her considerable help with field work. Acknowledgements are also due to Dr. P. Banham for the opportunity to discuss the results. Finally, he would like to thank J. Rose, for his advice and supervision throughout the project.

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Bull. geol. Soc. Norfolk, 30, 77-78 (April 1978)

REPORT ON A FIELD MEETING AT DOBB'S PLANTATION, WROXHAM (TG 273158), SEPTEMBER 1977

P.G. CAMBRIDGE*

The decision to attempt a dig in this area was taken because of the special interest of the Icenian Beds in the Bure Valley. At one time there were a number of pits near Belaugh, Wroxham, Coltishall and as far up the valley as Aylsham. Many of these pits were originally worked for chalk and the overlying beds, mainly pebbly sands, were dumped back into the pit. The pebbly sands were shelly in parts and it was noted that the bivalve, Macoma balthica was present in the upper beds only. For this reason early writers suggested that there was an overlap of the Norwich and Weybourne Crags in this area.

The area chosen was a small tributary valley of the Bure, Dobb's Beck, with a line of several pits, now overgrown, marking the outcrop of the Chalk. The most southerly of these, Limekiln Hole, alongside Dobb's Lane, was recorded by Woodward (1881) who noted casts of shells in ironstone. He noted that the next pit, "three furlongs to the north" showed shells in abundance and gave the following section:

			Feet
	3.	Pebbly gravel with shells up to the surface	6
Upper Crag	2.	Laminated clay	1/2
	1.	Shell bed, sand and gravel	2

Chalk with flints.

It was planned to excavate a section in this pit but difficulty

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was experienced in deciding the exact site. A large pit was located in the area marked on the map as Dobb's Plantation. The pit is largely backfilled and has mature trees growing in it but traces of shells were found near the eastern face and work started at this point. Digging was in a series of steps starting from the base of the pit. By midday the surface of the chalk was exposed about halfway up the slope and the lower part of the digging was then abandoned. With the aid of fresh reinforcements from the Ipswich Group the upper part of the section was cleaned and widened, offering a good working section in shelly Crag. After this was measured and recorded, members collected specimens and samples, a series of which is now in the museums at Ipswich and Norwich and in the author's collection. Details of the section are given elsewhere in this Bulletin.

Our thanks go to Mr. Trafford, of Trafford Estate for kind permission to examine the site, which it should be noted is on private land and needs permission to visit.

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Bull. geol. Soc. Norfolk, 30, 79-91 (August 1978)

A SECTION IN THE "BURE VALLEY BEDS" NEAR WROXHAM. (TG 273158)

P.G. CAMBRIDGE*

The section was excavated in September 1977, a description of which has already been given (Cambridge, 1978), and is illustrated in Fig. 1.

The History of Research on the Bure Valley Beds

The fossiliferous, pebbly sands and gravels of the Bure Valley were separated from the Norwich Crag by S.V. Wood and F.W. Harmer because of the occurrence of *Macoma balthica*. They regarded them as lower glacial and in 1866 gave the name Bure Valley Beds. Harmer (1894) wrote: "The late Mr S.V. Wood and I have classed the Bure Valley Gravels as the lowest horizon of the Glacial Series. H.B. Woodward of the Geological Survey regards them as belonging to the Crag period." They were recognised as marine, "the pebbles water-worn and rounded .... of a dark red colour."

On the other hand Prestwich (1871) divided the Icenian into Norwich Crag, Chillesford Clay and Westleton Shingle. He regarded most of the fossiliferous beds, with or without *Macoma balthica* as Norwich Crag. His Chillesford Clay, which Harmer also considered represented a well marked horizon, is not now recognised outside the type area near Chillesford and Aldeburgh in Suffolk. Reid (1890) commented "such laminated clays are characteristic of the Pliocene (sic) beds of Norfolk, they are not confined to one horizon, they were not all deposited at one particular time and their absence is not necessarily the result of denudation". Much of Prestwich's Westleton Shingle in the area would be classed with the Bure Valley Beds.

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Similar deposits with M. balthica on the coast were called the Weybourne Crag and in the early days their relationship was in dispute. Thus Prestwich correlated the Weybourne Crag with the Norwich Crag while S.V. Wood jr. considered it should alternate with the glacial deposits. Harmer in dividing up his Icenian period placed the Weybourne Crag at the top of the series as the youngest division of the Crag characterised by the first appearance of M. balthica which he designated as the zone fossil. This fitted in with his assumption that the Crags were deposited in a series which were geographically progressing to the North. Since the Bure Valley Beds also contained M. balthica they were considered the inland equivalent of the Weybourne Crag.

In the Lexique Stratigraphique the Bure Valley Beds are considered as "The inland equivalent of the Weybourne Crag which occurs on the coast, having the same fauna". (Baden-Powell 1963).

It was noted quite early (Woodward 1881) that M. balthica occurred only in the upper beds of the Bure Valley Beds leading to the suggestion that at this point the Weybourne Crag overlapped the Norwich Crag. This strengthened Harmer's interpretation of the Crag sequence with Red Crag seen resting on Coralline at Ramsholt Cliff, Icenian on Butleyan Red Crag at Chillesford and Weybourne Crag on Norwich Crag in the Bure Valley.

Until comparatively recently no further work has been done on the Bure Valley Beds, because of the overgrown condition of the exposures. Harmer (1920) wrote "Unfortunately none of these sections is now accessible". No new sections have been reported since then. However, West (1968) published a table of Lower Pleistocene stages based on pollen spectra in which essentially the Weybourne Crag was shown as the same

age as the Norwich Crag. The main difficulty to acceptance of this view is the complete absence of M. balthica in the rest of the Icenian with no apparent physical barriers to its spread. Accepting that the pollen flora is the same there is still no reason why the marine beds with M. balthica should not be younger than those without and the succession in the Bure Valley would seem to bear this out. In this view the Weybournian marine stage could be described as late Pastonian in terms of terrestrial pollen stages, a compromise dictated by the fact that biostratigraphical units tend to differ when a different Phyllum is used.

In 1977 P.E.P. Norton investigated the mollusca of another pit near Wroxham (personal communication) but the results have not yet been published. It is clear that this is an important area in determining the Icenian stratigraphy and further work is justified.

Description of the section

The surface of the Chalk showed no unusual features. The marine Crag consists of 1.35 metres of sandy gravels with several distinctive shelly beds. There were no sharp divisions between the various gravels. The lowest bed consisted of light coloured very sandy gravel with numerous well preserved shells, especially Macoma. This is followed by half a metre of badly sorted gravel, including ovoid, well rounded flints with chatter marks; angular flaked flints and detached flakes, some very fresh looking; eroded flints possibly from a land surface; chalk fragments. In the smaller pebble fractions quartz/quartzite pebbles are not uncommon. Small pebbles were very abundant in this layer but very large, unworn flints up to 30 cm across, also occur.

At 50 to 60 cms above the Chalk is an intermittent ferruginous layer of flattened concretions. Similar concretions are also scattered

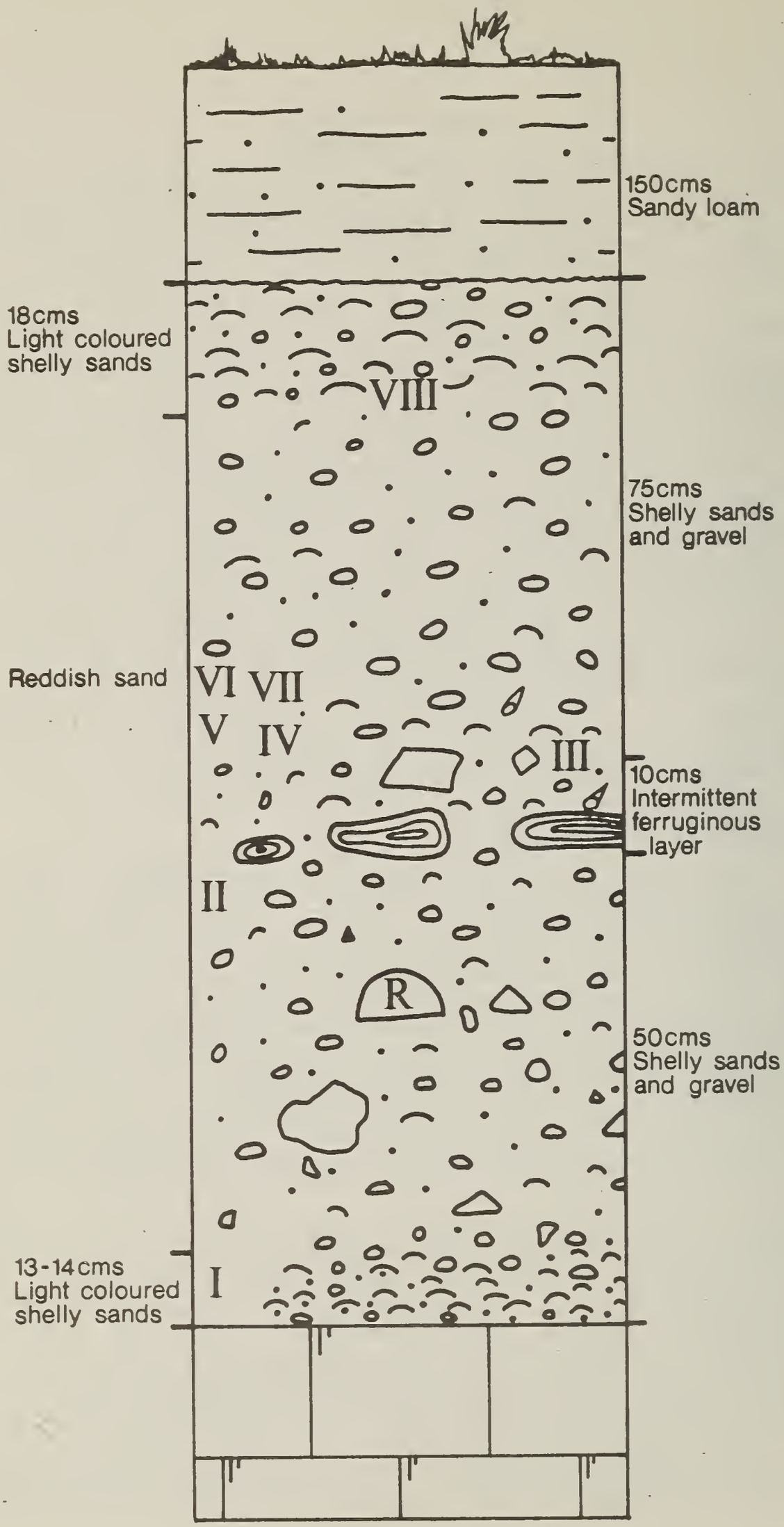

Fig. 1 BURE VALLEY BEDS

DOBB'S PLANTATION, NR WROXHAM HALL

Roman numerals indicate positions where samples were taken. R = "rostrocarinate" flint.

throughout the section. The sand and gravel at this horizon is distinctly red in colour. Finally some 75 cms of shelly sands and gravel follow with a distinct bed of light coloured worn shells at the top.

Over the Crag is a thick layer of sandy loam, probably hillwash and soil from the ploughed field above. A scatter of pebbles on the field included many flints, as well as quartz/quartzites and pieces of very fossiliferous crinoidal chert.

The lower part of the gravels is decidedly more angular than the upper and large flints persist to about 70 cms above the Chalk. There is no 'Stone Bed' on the Chalk as is frequently the case at the base of the Crag.

Palaeontology

Samples averaging about 4 kgs each were taken, especially from the more shelly portions of the gravels.

Sample numbers are shown in Roman numerals in Fig. 1. Samples III and V were ironstones; the faunas from the other samples are listed in Table I. Considering the small size of the samples the fauna is a large one. Samples VI and VII can be considered to come from one bed. Where less than five specimens were found the actual number is shown in the table. The fauna throughout is dominated by the bivalve *Macoma*.

Sample I.

The basal bed is especially rich in vertebrate remains. Apart from fragmentary mammalian remains the fish fauna is much larger than is usual in the Icenian. The shark *Hexanchus* is recorded from the Red Crag but apparently not from the Icenian and there are several other fish teeth not in the table as they are not yet fully identified. It is possible that some of the teeth are derived. In fact the two very

small fragments of Turritella incrassata are probably also derivative.

Sample II.

The shells are very fragmentary and worn.

Sample IV.

A large, well-preserved fauna. One example of Macoma with paired valves.

Sample VI and VII.

The gastropods seem well-preserved and include Beringius turtoni which is not recorded from the Icenian although found in the Red Crag and also as a recent species. Many of the larger bivalves are very worn and rounded but some quite fresh juveniles occur.

Sample VIII.

Many well-preserved shells.

Conclusions

The fauna as a whole is similar to that of many other Icenian sections, and would certainly be larger if further samples were examined. Woodward's early list of 1881 included only 15 species. The section is not so easy to interpret as that given by Woodward because the thin seam of laminated clay which divided his Bed 3 from Bed 1 was not present. However this may have been merely a local phenomenon and the clay might be present elsewhere in Dobb's Plantation pit.

The presence of Macoma balthica in the top of the section suggests correlation with the Weybourne Crag while the lower section bears some resemblance to the section in Norwich Crag at Blake's pit (see Bulletin No 27). In both the lower beds contain material which is suspected of being derived from earlier Crag beds. Both Nucella and Littorina are uncommon while Chlamys opercularis and Venus fasciata are common as at

Bramerton and Whitlingham. Rostrocarinate flints occur at both sites.

Sample 4 resembles the fauna of the Upper Shell Bed at Bramerton in some respects, such as a larger number of Littorina and Nucella and the appearance of Macoma calcarea which may indicate some cooling. The absence of some Bramerton species may result from a difference in facies. In the Yare Valley at Postwick Village, Bramerton and Whitlingham, the shelly Crag is followed by ferruginous beds without fossils and it is just possible that these compare with the ferruginous layer and red gravels in the middle of the section at Dobb's Plantation.

Rostro-carinate flints

Like most Crag deposits the pebbles consist almost wholly of flint, although there is a small proportion of chalk pebbles especially in the lower part of the gravels. The pebbles of the lower gravel are also considerably more angular than the upper and include a number of 'flakes' and 'cores'. These terms are more generally applied to artifacts and are used here for want of better names, but without implying any kind of artificial origin. Pebble size varies considerably and some very large flints occur. Some of these are unworn Chalk flints with cortex still present, other were cores with many flakes removed, patinated and ironstained. One of these, marked (R) in Fig. 1., approaches the form described as 'rostrocarinates'.

At the beginning of the century many prehistorians were preoccupied with finding evidence of man's presence in the Crags. J.R. Moir carried out a series of special excavations in the Red and Coralline Crags, and figured a number of crudely flaked flints which were claimed to be of human origin. Other evidence ranged from the ridiculous (the shell portrait from Walton-on-the-Naze) to the disputed (shark teeth perfora-

TABLE I . Faunal List

Bivalves	SAMPLE NUMBERS I	II	IV	VI	VII	VIII
Abra sp	3	-	-	-	-	-
Acila cobboldiae (J Sowerby)	1	-	X	-	-	-
Anomia (s.l.)	X	-	-	-	-	-
Arctica islandica (L)	X	-	X	X	X	X
Astarte (Tridonta) borealis (Schumacher)	2	-	X	-	-	-
A. (Tridonta) montagui (Dillwyn)	X	X	X	-	X	-
Cerastoderma edule (L)	X	-	X	X	X	X
Chlamys opercularis (L)	X	-	-	-	-	-
Corbula (Varicorbula) gibba Olivi	2	-	X	1	3	4
Divaricella (Lucinella) juttingae Spaink	2	-	-	-	-	-
Donax (Cuneus) vittatus (Da Costa)	-	-	4	-	-	2
Hiatella arctica (L)	2	-	4	-	1	-
Macoma balthica (L)	-	-	-	-	-	X
M. calcarea (Gmel)	-	-	4	-	-	-
M. obliqua (Sowerby)	X	X	X*	X	X	2
M. praetenuis (Wood)	2	-	X	4	4	-
Mactra corallina L	-	-	-	-	-	3
Mya (Arenomya) arenaria L	2	3	X	X	X	X
Mytilus edulis L	X	3	X	X	X	X
Nucula nucleus L	-	-	1	-	1?	-
Phacoides (Lucinoma) borealis (L)	-	-	2	-	-	-
Scrobicularia plana (Da Costa)	1	-	-	-	-	2
Spisula sp	2	-	2	-	-	1
Venus (Clausinella) fasciata da Costa	X	2	-	-	frag	-
Yoldia myalis (Couthouy)	X	1	X	1	1	3

X* One example with paired valves.

Table I. continued

Gastropods	I	II	IV	VI	VII	VIII
Amauropsis islandica (Gmel)	-	-	1	-	2	1
Beringius turtoni Bean	-	-	-	-	1juv	-
Boreoscala	2	-	-	-	-	-
Calliostoma	1	-	-	-	-	-
Littorina littorea L	X	-	X	3	4	X
Lora sp	-	-	1	-	-	-
Melampus (Ellobium) pyramidule (Sowerby)	-	-	2	-	-	2
Natica s.l. sp	-	1	X	1	-	2
Gastropod borings in bivalves	-	-	X	-	-	-
Neptunea antiqua (L)	-	-	-	-	-	1
Nucella lapillus (L)	X	4	X	-	-	1
Turritella communis Risso	-	-	2	1	-	-
T. incrassata (J Sow)	2	-	-	-	-	-
Other Invertebrates						
Crustacean claws	-	-	1	-	-	1
Balanus balanus L	X	X	X	-	-	X
Balanus sp	X	X	X	-	-	X
Regular echinoid spines ("Echinus")	X	-	-	-	-	-
Irregular echinoid spines ("Echinocardium")	X	-	-	-	-	-
Polyzoans (Impressions on shell)	-	-	1	1	-	-
Cliona sp	X	-	X	X	4	X
Vertebrates						
Cervid, fragment of antler	1	-	-	-	-	-
Elephant, ivory fragments	2	-	-	-	-	-
Elephant, tooth fragment	1	-	-	-	-	-
Rodent, incisor	1	-	-	-	-	-
Hexanchus sp., tooth	1	-	-	-	-	-
Chrysophrys sp., teeth	3	2	-	-	-	-
Raia sp., dermal tubercle	1	-	-	-	-	-
"Platax woodwardi" agg.	X	-	-	-	-	-
Gadoid otoliths	4	-	1	-	-	-
Fish vertebrae	1	-	1	-	-	1
Derived Chalk fossils	X	-	X	-	2	-

ted at the point of balance. Most of the supposed evidence for the presence of man in the Crags is discussed by Sainty (1929). To date the only known human remains is a jawbone from the Red Crag at Foxhall, near Ipswich. It cannot be proved whether this was actually a true Red Crag fossil as its present whereabouts is unknown.

Lankester (1915) selected from Moir's collection a number of beak shaped flints, and one of these from the Norwich Crag at Whitlingham was selected as a test specimen. The main features of this 'implement' type were a flat lower surface, supposedly produced by one cleavage blow, with the two sides trimmed to form a keel or carina, a wide solid butt and a beaklike point at the other end. Ideally the projected form was symmetrical, although it was admitted this was not always achieved.

In the following decades man's presence in the Crag was discounted on the grounds that the deposits were too old, or that the climate at the time was too cold. Since then artifact-producing primates have been discovered in Africa in coeval deposits. The presence in the Crag of land and freshwater shells now found in North Africa and around the Mediterranean, suggests that the land climate was by no means unfavourable. If slow-moving mammals like the hippopotamus could reach the area during the Eemian Interglacial why should more mobile primates not do so? With this in mind the author collected flaked flints from the base of the Norwich Crag in the area around Whitlingham and Bramerton. Examples showing the general features of a rostrocarinate were not uncommon but none was as perfect as the type specimen. Indeed every gradation occurred between implement-like forms and rough flints. All had one feature in common; they were formed from large, rounded and worn flints, broken to give a plano-convex shape. The flat ventral

surface was generally the most heavily patinated and there were often a number of short, parallel scratches on it. Lankester (1915) noted these scratches and suggested they might have been caused by use or by ice action.

One thing was apparent. The rostrocarinates could not have been purposefully formed in the way that was suggested. There is a difference in the patination of the flake scars which shows that they were not all made at the same time. The flat ventral surface was always more heavily patinated but there are also differences between the scars on the sides and dorsal surface. If the specimens are not artifacts then how were they formed?

The specimen (R) at Dobb's Plantation was found in situ with the plane face downward and is so battered that most of the original cortex is removed. Small scratches are present on the ventral surface, 15 to 20 mm long, in two series at an angle of about 30° to each other. Occurring as it does in a sandy gravel, the ventral face would have rested on points of underlying flint pebbles and any movement with pressure from above could cause the scratches observed. Pressure against underlying flint pebbles near the edges would cause flakes to be detached at a high angle to the ventral surface and so form the carina. Such movements might have been caused by wave pressure during deposition, or by subsequent movements in the deposit caused by glacial loading, solution of carbonates or other causes. Cases of natural flaking of flints in subsoil are discussed at length by Warren (1923). Several very fresh looking flakes were found in the lower gravel at Dobb's Plantation suggesting that some flaking subsequent to deposition has occurred.

Whether the 'rostrocarinates' were formed entirely in situ in the base of the Crag cannot be proved. The battering of some examples suggests a varied history. A very considerable time elapsed between the emergence of the Chalk surface and the deposition of the early Pleistocene Crag. The large number of a similar shape in the Stone Bed or near the base of the Norwich Crag suggests a common origin. It can be concluded that human agency in making the Norwich Crag rostrocarinates is disproved by the differences, in the same specimen, of patination of flake scars.

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DEPOSITS MARGINAL TO THE RED CRAG BASIN

R.G. Dixon*

Introduction

Several deposits, such as the Creeting Beds, lying to the west of the main Red Crag basin have been assigned a Red Crag age and a marine origin by many workers. A recent examination of these deposits has shown that some previous assumptions may be unfounded, and that the age and origin of some beds is doubtful. This brief contribution is in part a review of previous major work on these deposits. It also serves to introduce some quantitative results, which were all too lacking in the earlier literature. It will become apparent, moreover, that a great deal of work still needs to be carried out before firm conclusions can be reached or should be accepted.

The Creeting Beds

The age and origin of deposits to the west of the main shelly Red Crag mass are somewhat enigmatic. The best known sections are those at Creeting and Bramford, but the deposits can be traced from Stowmarket and Wickham Market to the Grundisburgh district. For the most part the sediments are clean, white, unfossiliferous sands with a basal pebble bed, and overlie Reading Beds, Thanet Sands and, further to the west, Chalk. The sands are overlain unconformably by quartzose gravels (White Ballast) and silts, which have been dated as Beestonian (M. Pleistocene) by Turner (in Mitchell *et al* 1973).

The basal pebble bed commonly 0.3m thick, consists of flint pebbles in a brown, muddy fine sand matrix. Phosphatic nodules, shark's teeth,

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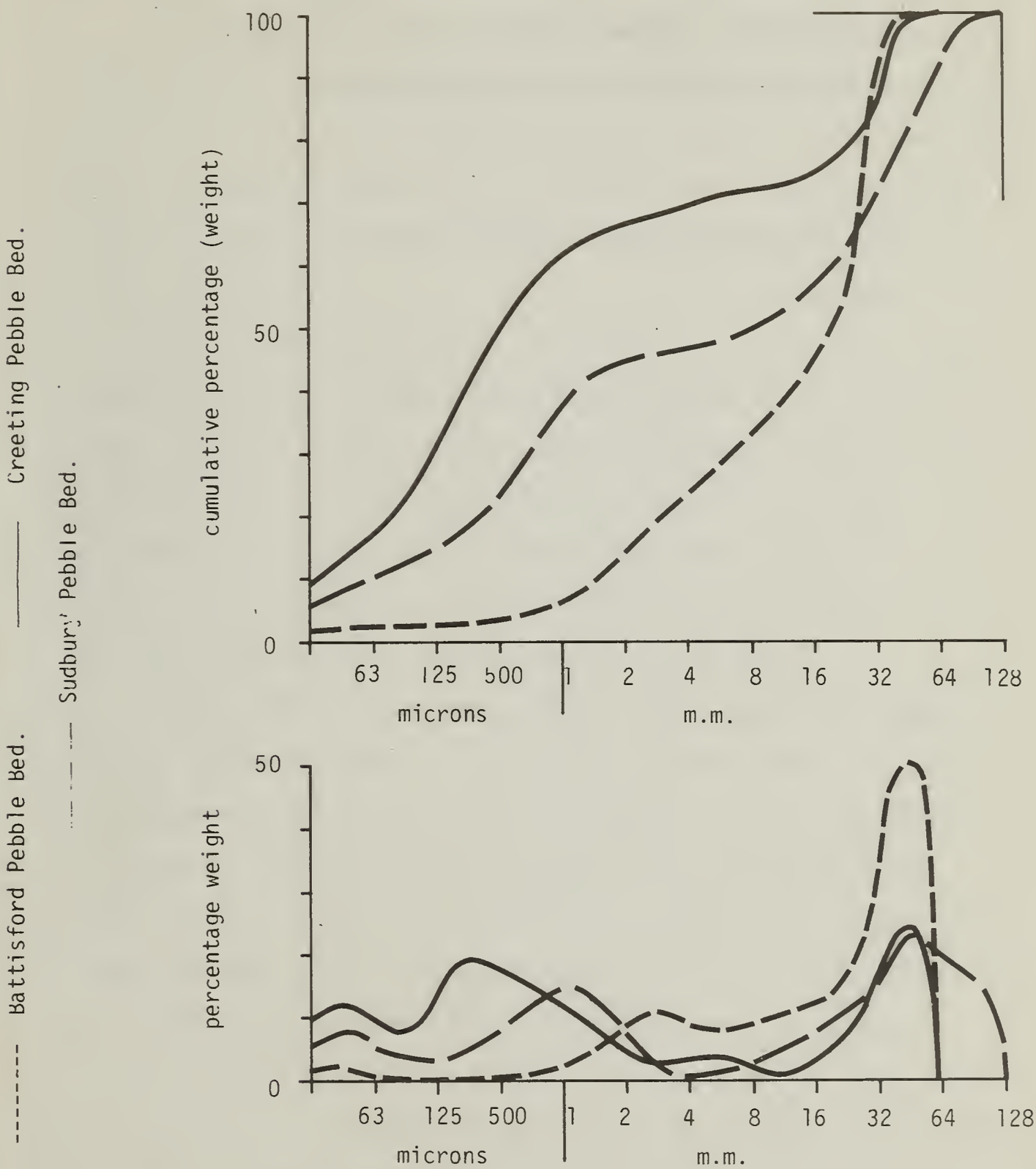

Figure 1. Particle size distribution curves of Battisford, Creeting and Sudbury Pebble Beds.

OMMISSION

This diagram should be included with the paper by R.G. Dixon "Deposits marginal to the Red Crag Basin" as published in Bulletin No. 30 (1978).

The editor apologises to the author for the ommission.

fragments of ray palate and bone also occur, having been derived from the underlying Tertiary deposits.

The pebble bed is generally similar to that at Battisford, but differs, however in containing no shell debris or even casts or moulds, such as are common at Battisford and in basal deposits of the Lower Red Crag. The Creeting pebble bed also contains a much higher mud content than its supposed equivalents at Battisford or in the Lower Red Crag, which contain no mud.

The overlying Creeting Sands are well sorted fine or medium sands, sometimes with small or medium scale false bedding, and are typically 3m thick. The sands are very similar in lithology and structure to fluvuiglacial deposits at Haugh Lane, Woodbridge, which differ, however, in containing a comminuted, abraded and strongly etched, derived Red Crag fauna. The Creeting Sands do contain foraminifers in a similar state of preservation, but less commonly, and no mollusc debris.

Whitaker (1874), Reid (1890), Boswell (1928) and others suggest a Red Crag age for the deposits, based largely on the similarity to the Red Crag, and dissimilarity to the drift deposits, and the occurrence of phosphatic nodules at the base. However, the Creeting Beds are neither red, nor crag (i.e. shelly sand), the state of the foraminifers suggests almost certain derivation (and only indicate a maximum age for the deposit), and phosphatic nodule beds can occur in any deposit resting on the London Tertiary series. The pebbles are of local origin, and thus indicate a pre-Baventian age, for it is not until the Baventian that exotic pebbles became common in the East Anglian Pleistocene (Hey 1976).

Spencer (1967) suggests that the sands are of Red Crag age, since

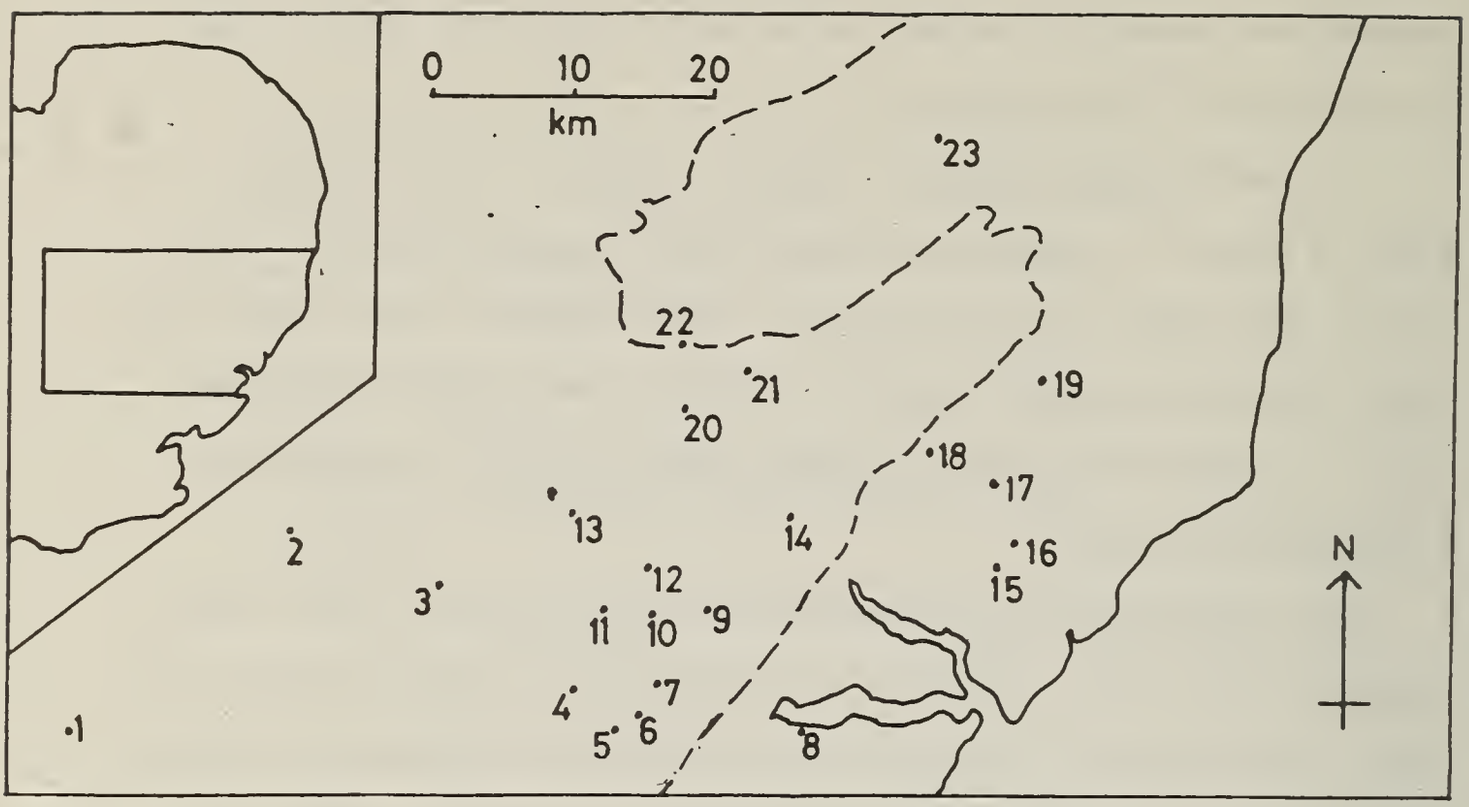

Figure 2. Map of localities referred to in text.

-------- approximate limit of shelly crag.

1	Thaxted	13	Monks Eleigh
2	Stoke by Clare	14	Bramford
3	Sudbury	15	Newbourn
4	Nayland	16	Waldringfield
5	Boxted	17	Woodbridge
6	Langham	18	Grundisburgh
7	Stratford	19	Wickham Market
8	Mistly	20	Battisford
9	Raydon	21	Creeting
10	Shelley	22	Stowmarket
11	Polstead	23	Stradbroke
12	Hadleigh		

they contain a supposedly Villafrancian deer fauna, including Cervus falconeri, C. tetraceros with Ursus ?arvenensis and Castor ?veterior. This fauna possibly indicates merely a Lower Pleistocene age (not just Red Crag), but could equally well be derived, and correlation cannot be certain.

More reliable evidence of a marine origin is recorded by Markham (1971; pers. comm.) who notes the rare occurrence of articulated Mytilus edulis, barnacle fragments, a questionable Neptunea contraria and casts and moulds of other molluscs from the pebble bed at Bramford. If the Mytilus are articulated, as Markham suggests, they are unlikely to be derived, and tend to suggest a littoral origin for the pebble bed. But this evidence is still not conclusive of a Red Crag age. Spencer (1967) records the rare casts of Turritella. Also, trace fossils, comparable but not identical to those found in the Red Crag (S.S.), have recently been found at Bramford. This evidence would tend to confirm a marine origin for these deposits.

The Battisford Beds

The Creeting Beds do provide a link between the Red Crag and a fossiliferous pebble deposit at Battisford, which rests unconformably on Chalk. Some 3.5m of pebbles are overlain by 1.8m of pale grey/yellow sands, which are overlain by glacial quartz sand and gravel, and by till. The pebbles are predominantly of flint, but phosphatic nodules occur and there is much derived Upper Cretaceous material - belemnites, crinoid ossicles. Cidarid spines and Inoceramus fragments, though Chalk pebbles are uncommon. Indigenous and derived vertebrate remains are also common.

The mollusc assemblages are not comparable with assemblages later

than Thurnian (i.e. early Norwich Series), but indicate an age younger than Gedgravian. All the molluscs recorded from the pebble bed are to be found in the Red Crag, and a Red Crag age is assumed for them.

Table 1 shows the percentage frequencies of molluscs obtained in a sample from the Battisford Pebble Bed (method after Norton, 1964). It can be seen that nearly 20% of the shells were too worn to be identified to specific level; this indicates a high degree of transport, and there is little doubt that much of the assemblage is allochthonous. The assemblage compares most favourably with certain assemblages from Lower Red Crag in the Waldringfield/Newbourn district, where a Venerupis-rich sublittoral shell gravel association occurs. However, Mytilus edulis occurs in high frequencies, and many Mytilus valves are articulated. This suggests that many of the sublittoral shells have been transported to a shallow water or littoral environment. The high frequencies of large, easily rolled gastropods, e.g. Neptunea and Turritella can also be accounted for by preferential transport and their hydrodynamic behaviour. The presence of ?Arenicola tubes is supporting evidence of shore-line conditions. The presence of articulated shells, e.g. Macoma obliqua and Mytilus edulis, indicates that derivation from a Red Crag source is extremely unlikely. The sands, on the other hand, contain no shell debris, and the finely preserved sedimentary structures suggest that no decalcification took place. In other words, no shell debris was available for deposition. However, small trace fossils identical to a type found in the Red Crag are abundant at certain horizons, invalidating any suggestion of reworking and confirming an onshore or nearshore marine environment.

Intertidal, small scale, asymmetrical ripples, climbing ripples

and some symmetrical ripples occur throughout the fine sands. They indicate tidal ebb and flow conditions towards the north-northeast (020°) and south-southwest (200°), and deposition by currents with velocities of about 0.2m/sec. Clay laminations, which separate ripple trains, dip a few degrees to the north-northeast, which was also the dominant flow direction (about four times more ripples show this direction than 200°).

To the southwest of Battisford are several isolated outcrops of similar deposits. Pebble beds containing flint, phosphatic nodules, shark's teeth and bone are recorded from Hadleigh, Nayland, Boxted, Mistly, Langham, Stratford, Shelly, Polstead, Rayden, Monks Eleigh, Thaxted, Sudbury, Stoke-by-Clare and Shalford (Whitaker 1874, 1878, 1885; Reid 1890; Boswell 1927, 1929; Boswell and Double 1922) and possibly at Rothamstead (Dines and Chatwin 1930). At these localities pebble beds 0.25m-0.5m thick are usually overlain by unfossiliferous pale or ferruginous sands with iron bands. However casts of Cardium angustatum, a fossil known only from the Red Crag, is recorded from sands at Hadleigh, and Nucella lapillus from Stoke-by-Clare. Reid (1890) and Boswell (1929) list several species from Sudbury, all of which are recorded from the Red Crag.

The majority of shell debris is, however, fragmentary and unidentifiable, except for some more resistant calcite forms, such as Pecten, and undoubtedly the composition of the pebble beds owes much to the underlying Eocene and Chalk. At Shalford (grid ref. TL 722292) a small number of worn, abraded and chemically etched foraminifers and some mollusc debris is present in greenish sands, which underlie the pebble bed; local iron cemented decalcified sands contain abundant casts of

Table 1. Percentage frequencies of molluscs from the Battisford Pebble Bed.

Group 1 : Intertidal rocky shore	
Diodora apertura	1.7
Trivia coccinelloides	0
Mytilus edulis	6.2
Total	8.7
Group II : Intertidal sandy shore	
Cerastoderma edule	1.2
Mya arenaria	3.7
Total	4.9
Group III : Infralittoral	
Calyptraea chinensis	0
Emarginula reticulata	0
Lutraria elliptica	0
Zirfaea crispata	3.8
Total	5.8
Group IV : Sublittoral shell gravel	
Capulus ungaricus	2.5
Anomia patelliformis	0
Glycimeris variabilis	3.3
Ostrea edulis	0
Pecten maximus	0
Venerupis rhomboides	7.9
Venus casina	0
Total	15.7

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Table 1. continued

Group V : Sublittoral muddy sand		
Aloidis gibba		1.2
Nucula nucleus		0
Total		1.6
Group VI : Sublittoral clean sand		
Natica catena		0
Callista chione		0
Dosinia exoleta		2.5
Total		3.7
Group VII : Sublittoral silty/mud tolerant		
Turritella triplicata		10.0
Cyprina islandica		0
Total		10.4
(**Group VIII : Sublittoral high boreal gravel/mud epifauna**)		
(none)		
Group IX : Low/mid boreal gravel/mud epifauna		
Neptunea contraria		4.2
Total		4.2
Group X : Miscellaneous		
Astarte digitaria	habitat unknown	0
Chlamys opercularis	various substrates	0
Venus ovata	" "	2.1
Total		2.9
Group XI : Unidentifiable		
Natica		3.4
Astarte		6.3
Cardita		0

Table 1. continued

Cardium	1.7
Isocrassina	2.9
Nucula	0
Pholas	0
Spisula	2.9
Venus	0
Total	19.5
Group XII : Extinct	
Lacuna suboperta	0
Natica catenoides	0
N. multipunctata	0
Neptunea lyratodespecta	2.5
Nucella lapillus vulgaris	0
N. tetragona	0
Searlesia costifer	0
Astarte obliquata	0
Cardita corbis	0
C. scalaris	1.7
C. senilis	0
Cardium interuptum	0
C. parkinsoni	0
Ensis complanatus	0
Gastrana laminosa	0
Macoma obliqua	0
M. praetenuis	0
Nucula laevigata	0
Panopaea faujasii	0

Table 1. continued

Pholas cylindrica	4.8
Venus imbricata	2.1
Total	21.5
Total individuals	119
Total species	48
Percent of one individual	0.84
Individuals per kg	42

Also recorded : ?Arenicola
Serpula
Ditrupa
Balanophylia caliculus
Sphenotrochus intermedius

(0 = frequencies less than one percent)

Mya, Cardium and Mytilus - very similar to parts of the Upper Red Crag. The possibility and suggestion of reworking is too strong for a Red Crag age to be automatically assumed for these deposits. The Red Crag shells may only indicate an age for the source material for fluvio-glacially reworked sediment.

Summary and Discussion

Although similar, granulometric analyses of the Creeting, Sudbury and Battisford pebble beds show a marked difference. Cumulative frequency curves and histograms of mechanical composition from Battisford are very similar in shape to those from the Westleton Beds recorded by Hey (1967), and support the assumption of a littoral marine origin. Cumulative frequency curves and histograms from the Creeting and Sudbury deposits do not match, and their origin must be questioned; it seems that reworking is likely, but it is uncertain when or how. The Battisford Sands are also considered to be of littoral marine origin, on account of the well preserved sedimentary structures and trace fossils. A precise age, however, cannot be given for these sands, because no macrofossils are preserved, or were deposited.

Mollusc assemblages from the Creeting and Sudbury deposits do little to confirm or deny marine or other origins for the beds, largely because only part (if any) of the original assemblage is still preserved, and the shells often show signs of considerable wear. The Battisford fauna does, however, promote a good correlation with the Red Crag.

Finally, the geographic position of the Battisford deposits suggests a relationship with the Stradbroke trough rather than the Red Crag basin. Similarly the Sudbury - Lavenham - Monks Eleigh deposits all lie on a southwesterly extension of the trough axis. Furthermore, dominant

flow directions at Battisford are towards the trough axis and not towards the Red Crag basin. The strong implication is that the Chalk ridge separating the Red Crag basin from the Stradbroke trough provided an effective emergent barrier between the two basins, and littoral deposits accumulated on its northwest and southeast flanks. Certainly the Chalk ridge outcrops at greater heights O.D. than the Battisford Beds at 45m O.D. However, at depth in the Stradbroke trough, from -15m O.D. to -39m O.D. at Stradbroke Priory, lie pre-Ludhamian sediments, which may also be correlated with the Red Crag (Beck et al 1972). The significant difference in heights above and below O.D. for the various deposits of Red Crag age appears problematical and cannot be readily accounted for.

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Bull. geol. Soc. Norfolk, 30, 105-112 (August 1978)

GRAVITY MEASUREMENTS IN THE WASH BY THE UNIVERSITY OF EAST ANGLIA

M. SOLA and P. N. CHROSTON*

Introduction

The aeromagnetic map of southern Britain (Institute of Geological Sciences 1965) shows a prominent magnetic anomaly situated over the Wash. The anomaly reaches a peak to peak (positive) amplitude of over 200 gamma and is one of the more distinct individual features in the complex belt of anomalies extending from Central England to North Norfolk. These magnetic anomalies are derived from sources within the sub-Mesozoic floor, and the relationship between the gravity and magnetic anomalies is of considerable geophysical interest. Gravity data for the mainland area has already been compiled by the Institute of Geological Sciences (see Gravity Survey Overlay Sheet No. 12), but the Wash was not included. In view of the prominence of the Wash magnetic anomaly we have extended the land gravity survey to include the Wash, and the method and results of the survey are presented in this note. The gravity measurements were made in 1972 and 1973, and further measurements have subsequently been made by the Institute of Geological Sciences (hereafter referred to as IGS). Our work is part of a programme of geophysical and geological studies of the sub-Mesozoic geology in East Anglia, and a preliminary account has already been published (Chroston and Sola 1974).

Survey method

Access

The gravity measurements were made on sand banks at varying states

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of tide. At low tide only the central part of the Wash has no exposed banks and about two-thirds of the Wash area can be covered satisfactorily with gravity readings. Access to the Wash was provided by the University research boat "Envoy", a 26 foot launch, and this is equipped with Decca navigator for position fixing. The meter was taken ashore (to the sand banks) by small boat, and readings taken as close to Envoy as possible. It is believed that sites could be located with an accuracy of ±20 m assuming no Decca positioning errors.

In using Decca a fixed positioning correction (provided by Decca) has been made but small variable errors (due to waves reflected back to earth by the ionosphere) may also be present. These are believed to be small, but a total positioning error of ±100 m is possible.

Instrumentation

The instrument used was a Worden Gravity Meter No. 180 owned by the University of East Anglia. The meter had been calibrated between the IGS calibration stations at the Cat and Fiddle Inn (near Macclesfield) and North Rode, and a calibration value of 0.09654 mgal/per dial division was adopted for the survey.

Base station

The IGS gravity reference station at King's Lynn (Free Bridge) was inconvenient for the survey and a temporary station was set up by the Y.H.A. building in King's Lynn close to the quay. Eight connections were taken between Free Bridge and the Y.H.A. station, and in addition, the Y.H.A. station was connected to the Norwich, Cromer and Swaffham gravity reference stations. A detailed description of the Y.H.A. reference station can be found in Sola (1974).

Data reduction

The Bouguer anomaly for each station was calculated in the usual manner (see e.g. Dobrin 1960). Special points with regard to various corrections are made below.

Drift correction

A linear rate of drift for the meter was assumed and tests showed that the drift was typically 0.02 mgal/hr. Because of the nature of the survey it was not possible to reoccupy the reference station except at the end of a day's work and the time between successive base readings was often 6 hours or so. The maximum drift during a work period was 0.14 mgal, and the minimum 0.05 mgal.

Elevation correction

A detailed, precision, gravity survey normally requires that the elevation of a station is known to an accuracy of better than 0.1 m. In this survey gravity readings were established at or very close to the actual sea level and the height for each station relative to the high water mark was calculated from the Admiralty Tide Tables. After this height had been established it was reduced to Ordnance Datum. This method was checked for accuracy by comparing calculated tidal heights with actual tidal heights as recorded on a tide gauge operated by Binnies and Partners Ltd., who were also working in the Wash. The results of the comparison are shown in Fig. 1, and it can be seen that the maximum difference is 0.5 metres. This error in elevation determination will lead to an error of 0.1 mgal in the calculation of the elevation correction.

An accurate knowledge of rock densities is usually essential to ensure an accurate calculation of the Bouguer and terrain corrections.

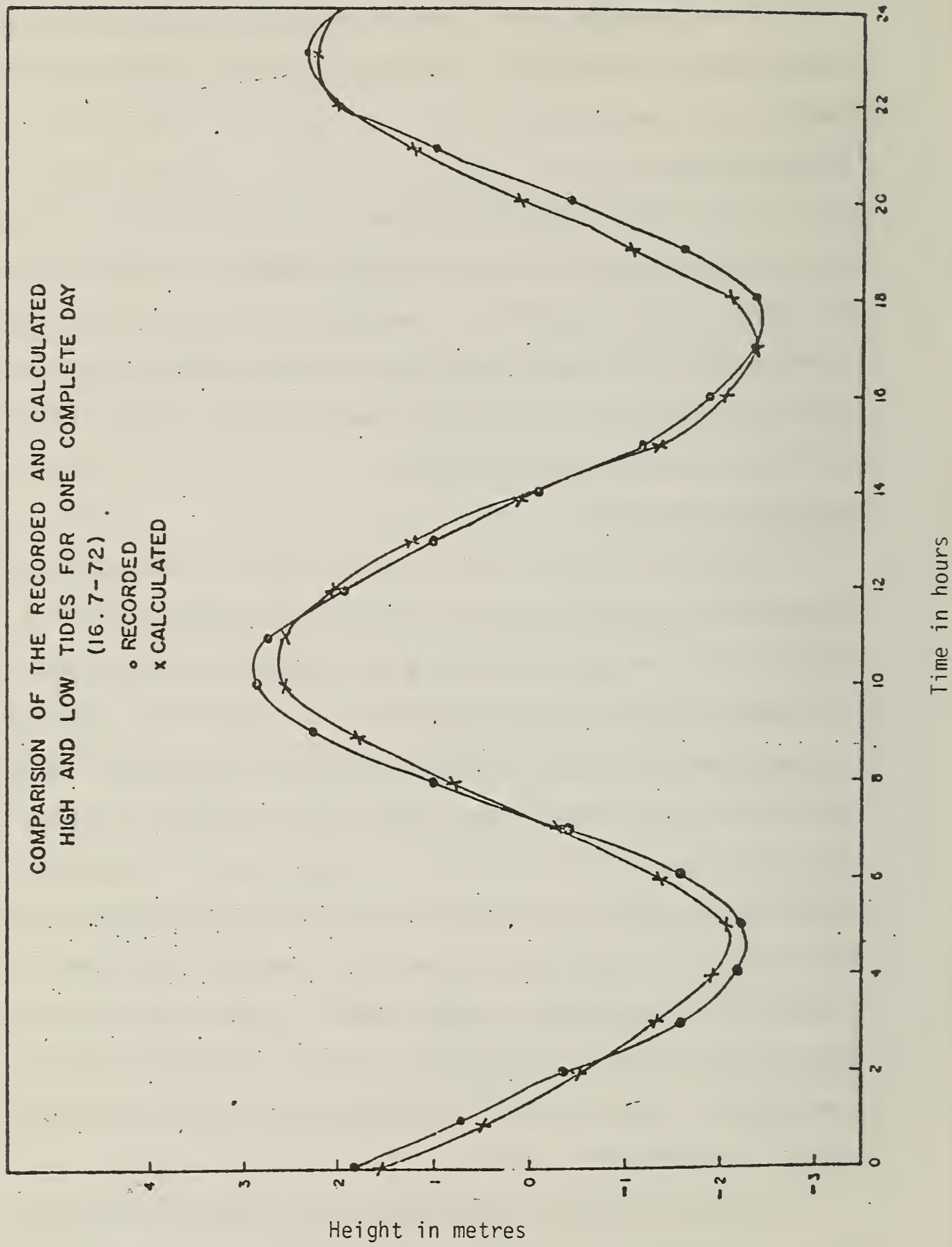
COMPARISION OF THE RECORDED AND CALCULATED
HIGH AND LOW TIDES FOR ONE COMPLETE DAY
(16.7-72)
o RECORDED
x CALCULATED
Height in metres
Time in hours
4
3
2
1
0
-1
-2
-3
0
2
4
6
8
10
12
14
16
18
20
22
24

Fig. 1

In previous work around the Wash, IGS have used values of 1900 -2100 kg m^{-3}, depending on the surface geology. Tables of density measurements given by Jakosky (1950), Dobrin (1960), and others, give densities of 2000 kg m^{-3} for sand, and we have used this value for the reduction density. In fact the maximum difference in elevation between Ordnance Datum and a gravity station is 3.38 metres and hence the combined free-air and Bouguer correction is very small. An error of 10% in choice of density would result in an error of less than 0.01 mgal in the calculation of the Bouguer anomaly.

Terrain correction

Tests showed that it was unnecessary to apply a terrain correction in this area.

Latitude correction

Theoretical gravity for each site was calculated using the International Gravity Formula (see e.g. Dobrin 1960). Latitudes were completed at one minute intervals and the change in gravity assumed to vary linearly between these latitudes. Assuming a positioning error of $\pm$100 m the theoretical latitude could be calculated with an error of less than 0.08 mgal.

Total error in the Bouguer anomaly

Applying the maximum likely errors due to instrumental drift, elevation, and positioning, a RMS error of approximately 0.1 mgal is obtained. The maximum possible error for any station is believed to be $\pm$ 0.15 mgal.

Results

Altogether some 122 gravity readings were made in the Wash. Their positions and a contoured map are shown in Fig. 2. It will be seen

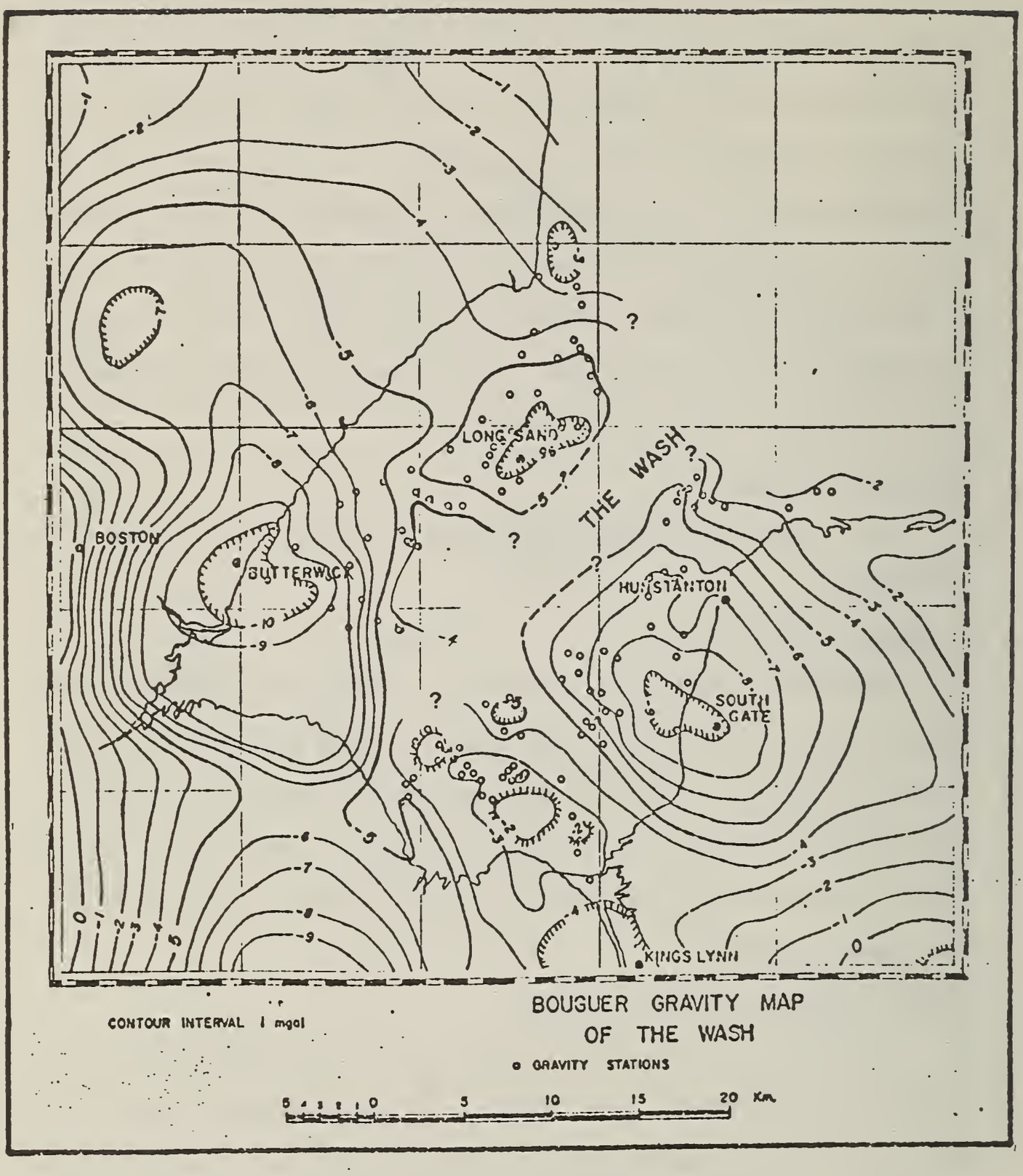

Fig. 2 Gravity map of the Wash based on University of East Anglia gravity stations.

that because of the distribution of the sand-banks the central part of the Wash is not covered. The results clearly demonstrate however a central axial high with a residual amplitude of at least 5 mgal which is also closely coincident with the Wash positive magnetic anomaly. The gravity lows at Southgate and Butterwick, both continue prominently into the Wash, only to be truncated by the central high.

A detailed geological interpretation of the Wash magnetic and gravity anomalies is to appear elsewhere. It is believed, however, that the anomalies cannot be easily explained by relief of the sub-Mesozoic floor. A satisfactory interpretation has to incorporate an intrusion within the sub-Mesozoic geology.

Acknowledgements

We thank Terry Adams for operating "Envoy", Messrs Binnies and Partners Ltd., for supplying the tidal data, and the Institute of Geological Sciences for providing descriptions of gravity reference stations.

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Bull. geol. Soc. Norfolk, 30, 113-118 (August 1978)

MARINE OSTRACODA FROM THE QUATERNARY NAR VALLEY CLAY, WEST NORFOLK

A.R. LORD* and J.E. ROBINSON*

Introduction

In the Nar Valley, west Norfolk a complex of Quaternary sediments includes a marine clay called the Nar Valley Clay, first described as Nar Valley Brickearth (see Rose, 1865). This clay lies or appears to lie between two tills, Lowestoft Till (Anglian) and so-called Gipping Till (Wolstonian); see Turner (1973, p. 14) for discussion. This deposit has been known to contain marine microfossils for over a century and a note listing ostracods and foraminifera was published in 1865 by T.R. Jones. More recently the palynology of the Nar Valley Clay has been studied by Stevens (1960) using material from boreholes located between East Winch and Narford Hall. On the basis of pollen and by means of comparison with then newly described pollen spectra from the Hoxnian interglacial site at Hoxne, Suffolk (West, 1956) a Hoxnian age was assigned to the Nar Valley Clay. In 1971 a number of slides containing calcareous microfossils, collected by Stevens from her borehole samples, were passed to one of us (ARL) by Professor B.M. Funnell for description. No sediment was then available and as the slides contained only a small number of ostracods with foraminifera, microscopic gastropods and lamellibranchs, echinoderm spines and occasional charophyte oogonia the material was put aside for later study. Recently a rich sample has become available, collected from a reservoir site at East Winch (TF690 150) by P.G. Cambridge and passed on by Professor Funnell. Further samples were also collected in the East Winch area in 1975 by

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Mr. H. Evans and given to J.E.R.

In view of the recent resurgence of interest in Quaternary ostracods and foraminifera as a result of work in and around the North Sea, the available Nar Valley Clay fauna is listed and discussed here.

The Ostracoda

Ostracods are microscopic bivalved crustaceans inhabiting all acquatic situations; they are particularly useful for environmental analysis.

The Stevens slides - of nine slides five were found to contain ostracods:

2.80 *Carinocythereis* cf. *C. antiquata* (Baird)
Leptocythere castanea (Sars)
Semicytherura cf. *S. sella* (Sars)

4.80 *Elofsonella concinna* (Jones)
Carinocythereis cf. *C. antiquata* (Baird)
Leptocythere sp 1.

5.80 *Carinocythereis* cf. *C. antiquata* (Baird)
Elofsonella concinna (Jones)

8.80 *Leptocythere pellucida* (Baird)
Semicytherura cf. *S. sella* (Sars)
? *Eucytheridea* sp. juv.

Unnumbered Slide A

Carinocythereis cf. *C. antiquata* (Baird)

The numbering on the slides does not appear to correspond with any borehole or depth mentioned in Steven's paper and the small number of specimens make this material of little use on its own. It is worth noting that Jones (1865) recorded the following species, which were

actually described by G.S. Brady in the same year:

Cythere arborescens Brady (= Aurila convexa (Baird))

Cythere aspera Brady (= Carinocythereis antiquata (Baird))

Cytheridea punctillata Brady (= Eucytheridea punctillata (Brady))

Normania carinata Brady (=? Loxoconcha rhomboidea (Fischer))
(actually described as
Cythere carinata)

The East Winch sample (TF690150) - contained a rich ostracod assemblage composed of:

Carinocythereis cf. C. antiquata (Baird) (males, females and suite of instars)	342 valves	64.0%
Semicytherura cf. S. sella (Sars) (males, females, instars)	1 carapace 60 valves	11.60%
Leptocythere sp. 1 (adults)	32 valves	5.90%
Leptocythere castanea (Sars) (males, females, instars)	28 valves	5.25%
Hirschmannia tamarindus (Jones) (adults)	1 carapace 25 valves	5.05%
Loxoconcha cf. L. rhomboidea (Fischer) (adults, instars)	1 carapace 16 valves	3.37%
Leptocythere pellucida (Baird) (adults)	15 valves	2.80%
Leptocythere sp. juv.	9 valves	1.70%
Elofsonella concinna (Jones)	1 juvenile valve	0.18%
Total:	3 carapaces, 528 valves	

Evans' material from East Winch - two samples were analysed:

i)	Carinocythereis cf. C. antiquata (Baird) (males, females and instars)	1 carapace,	25 valves
	Robertsonites tuberculata (Sars) (males, females and instars)		28 valves

Elofsonella concinna (Jones) (adulst and instars)	23 valves
Leptocythere pellucida (Baird (adults)	3 valves
Hirschmannia cf. *H. tamarindus* (Jones)	2 valves
Leptocythere sp. 1	1 valve
? *Krithe* sp.	1 valve
Total:	1 carapace, 83 valves

ii) *Robertsonites tuberculata* (Sars) (adults and instars)	17 valves
Elofsonella concinna (Jones) (adults and instars)	15 valves
Carinocythereis cf. *C. antiquata* (Baird) (adults and instars)	10 valves
Hirschmannia cf. *H. tamarindus* (Jones)	5 valves
Leptocythere sp. 1	3 valves
Eucytheridea bradii (Norman)	1 valve
Total:	51 valves

Discussion

The East Winch sample (TF690150) is rich and the presence of adults with suites of instars, especially of *Carinocythereis* indicates that the assemblage is in-situ and possibly approximates to the original biocoenosis. The assemblage reflects shallow, warm-water conditions, but for the presence of such a full group of *Carinocythereis* which indicates deeper water conditions of up to 20m. depth. *Elofsonella concinna* is a cooler water, more northerly species and although the presence of a single juvenile valve in the sample from TF690150 is not particularly significant, the occurrence of this species in larger

numbers in the two other East Winch samples indicates cooler or deeper water conditions. There are substantial differences between the larger East Winch assemblage and the two smaller ones, which contain relatively large numbers of Elofsonella concinna and Robertsonites tuberculata and fewer Carinocythereis.

The available assemblages differ from each other, but also differ from other British Hoxnian marine ostracod material. For example, the fauna from the Bridlington Crag of Dimlington, North Humberside described by Neale and Howe (1975, p. 404) is more diverse and reflects cooler water conditions. The Nar Valley Clay material also differs from Holsteinian assemblages described from north Germany and Denmark. In almost all the species listed here there are subtle differences in morphology between the living species and the Nar Valley Clay material, which may prove useful for correlation purposes.

Of particular interest is the depth significance of the ostracods. The Nar Valley Clay clearly reflects the high sea-level of an interglacial optimum, which was substantially higher than present sea-level (cf. the possibly Hoxnian Slindon Sands of Sussex). The faunas imply that the Nar Valley area during the Hoxnian was not simply a shallow embayment of the Wash and that the shoreline was at some distance from the present-day marine limit. We believe that a borehole re-investigation of the Nar Valley Clay is highly desirable for an improved understanding of the Hoxnian Interglacial in Britain.

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Acknowledgements

We are indebted to Professor B.M. Funnell and Mr. P.G. Cambridge of the University of East Anglia and Mr. H. Evans for providing material.

Appendix

The following foraminifera were also found in the East Winch (TF690150) sample:

Ammonia beccarii (Linne)	288	72.0%	size range	0.20-0.87 mm
Elphidium incertum (Williamson)	47	11.7%	size range	0.12-0.50 mm
Elphidium 'clavatum' Cushman	8	2.0%	size range	0.40-0.50 mm
Elphidium williamsoni Haynes	5	1.25%	size range	0.43-0.41 mm
Derived Cretaceous specimens	52	13.0%	size range	< 0.1 mm

Foraminifera were also found in the Steven's slides, but the only significant differences were the presence of Quinqueloculina seminulum (Linne) (size 0.43-0.90 mm) and Elphidium macellum (Fichtel and Moll) (size 0.87-0.56 mm), both of which occur around the British Isles at the present day but apparently close to their northern limit of occurrence. The same distributional consideration is applicable to Ammonia beccarii, the dominant species in the East Winch sample, which lives on the inner shelf, estuaries and also lagoons of less than normal marine salinity. The preponderance of this one species A. beccarii suggests reduced salinity and the presence of Quinqueloculina seminulum, which has little tolerance for salinity variation is probably not significant.

SECRETARY'S REPORT FOR 1977

There were five lecture meetings which together with the A.G.M. made six indoor meetings held during the year. They were: January, Mr P. G. Cambridge, 'Marine Deposits in the Southern North Sea in Neogene and Holocene Times, with Particular Reference to the Crag of East Anglia'; February, Mr R. Gallois, 'The Pleistocene History of West Norfolk'; March, a joint presentation by Professor B. M. Funnell and Mr N. B. Peake on 'Some Mineral Resources of Norfolk'; October, Mr P. G. Cambridge, 'The Geology of Malta'; November, Mr R. Toynton, 'Underground Water in the Norfolk Chalk - Is it all it's Cracked up to be?'; and December the Annual General Meeting.

The Meetings of February and October were held at the Norfolk College of Arts and Technology, Kings Lynn in accordance with the Society's aim to provide one meeting in each winter's programme at Kings Lynn.

Following the canvassing of members' opinion it was agreed to return to the Castle Museum, Norwich as the venue for meetings, and thanks are due to Mr Peter Lawrence and Mr Brian McWilliams for making this possible. Although meetings at the University were well attended members had expressed a preference for a more central location. It is probable that some meetings will be held at the University in future but the normal venue from now on will be at the Castle.

There were three committee meetings held during the year.

The last year has been a difficult one for me personally and it has meant that I had to rely a great deal on the support of the Committee. In particular I should like to express my thanks to Philip Cambridge who has taken a lot of the load from my shoulders for example, in printing the programme and sending it out to members. He also distributed

the Bulletin and prepared the agenda for the A.G.M. Thanks are also due to Dr Neil Chroston for stepping into the position of Editor and succeeding in publishing a Bulletin this year, when at one time it looked rather doubtful that one would appear at all.

This year's Committee is as follows:

Secretary	Dr C. J. Aslin
Treasurer	Mr P. G. Cambridge
Editor	Dr P. N. Chroston
Field Meeting Secretary	Mr P. J. Lawrence
Committee Members	Mr N. E. Dean
	Mrs E. Evans
	Mr N. B. Peake

December 1977 Christopher J. Aslin

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The Geological Society of Norfolk exists to promote the study and knowledge of geology, particularly in East Anglia, and holds monthly meetings throughout the year. Visitors are welcome to attend the meetings and may apply for membership of the Society. For further details write to the Secretary: Dr. C.J. Aslin, University Library, University of East Anglia, Norwich NR4 7TJ.

Copies of this Bulletin may be obtained from the Secretary at the address given above.

The illustration on the front cover is from Figure 80 (page 468) of the second edition of H.B. Woodward's "The Geology of England and Wales", published by G. Philip & Son, London in 1887. It is after a photograph of a Chalk pit at Whitlingham, near Norwich. The beds above the Chalk with flints, seen best to the right of the picture, comprise 4.5 to 6 m of Norwich Crag Series, made up from bottom to top of: Stone bed; False-bedded sand and gravel, with shells; Impersistent laminate clay, and shelly seam; and Pebbly gravel and sand, with seam of shells.

BULLETIN OF THE GEOLOGICAL SOCIETY OF NORFOLK

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Holocene stratigraphy of Brancaster Marshes
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Bull. geol. Soc. Norfolk, 31, (September 1979)

PALAEOENVIRONMENTAL ANALYSIS OF THE DOBB's PLANTATION SECTION, CROSTWICK (AND COMPARISON WITH TYPE LOCALITIES OF THE NORWICH AND WEYBOURNE CRAGS).

B.M. FUNNELL*

Introduction

This section was excavated by the Geological Society of Norfolk and the Ipswich Geological Group in September 1977 (Cambridge 1978a), and a preliminary account of the section and the molluscs recovered was given by Cambridge (1978b). Foraminifers were examined from the same samples from which the molluscs were obtained. The results of the examination of the foraminifers are here combined with a re-assessment of the mollusc data in order to interpret the environment in which these shelly sands accumulated.

Foraminifers

Foraminifers were examined from six samples. In view of the fact that they were dispersed in a large amount of mineral sand of the same size range, they were concentrated by flotation on carbon tetrachloride liquid. Only the 500 to 250μ m size fraction was analysed. (This size fraction has been consistently used by the present author for comparative work on Crag foraminifers.) The results are shown in Table 1, and illustrations of some of the most abundant species are given in Figure 1. Altogether 19 species were identified. The Arabic sample numbers in the Table correspond to the Roman numerals used in the section drawn by P.G. Cambridge (1978b, p. 82).

Sample 1, at 0.10m above the Chalk, is dominated by *Elphidiella hannai*, a Pacific species occurring on the west coast of North America at the present day, but very common in the North Sea in the early Pleistocene. It is followed in abundance by *Cibicides lobatulus*, a warm temperate to boreal or even arctic species commonly found attached to seaweed, and *Ammonia beccarii* a temperate intertidal or shallow sub-tidal species not present off the coasts of the British Isles during glacial periods. Several species of *Elphidium* are also present.

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Height of sample (m)	0.10	0.40	0.65	0.70	0.70	1.25
Sample No.	1	2	4	6	7	8
No. in sample	219	137	316	84	101	187
Ammonia beccarii	10	-	-	2	3	-
Buccella frigida	-	1	-	-	1	-
B. inusitata	1	1	1	-	-	-
Cibicides lobatulus	11	2	1	-	4	2
C. pseudougerianus	-	1	-	-	-	0
Elphidiella hannai	55	69	87	83	82	94
Elphidium alvarezianum	7	1	0	-	-	-
E. bartletti	-	-	1	-	-	-
E. crispum	-	-	1	-	-	-
E. excavatum clavatum	2	1	1	1	-	-
E.e. selseyense	0	-	-	-	1	-
E. frigidum	6	19	1	4	2	0
E. orbiculare	-	4	-	1	1	0
E. pseudolessonii	7	-	6	6	7	1
E. williamsoni	-	-	2	1	-	0
Guttulina lactea	0	1	-	-	-	0
Lenticulina sp.	-	-	-	-	-	0
Oolina hexagona	-	-	-	1	-	-
O. williamsoni	-	1	-	-	-	-

TABLE 1. Foraminifera from Dobb's Plantation
(CCl_4 float; 500-250μm fraction only; 0 = less than 1%)

At 0.40m above the Chalk sample 2 contains an even higher percentage of E. hannai, a lot of Elphidium frigidum a boreal to arctic species, some Elphidium orbiculare another boreal to arctic species, not found south of the Faeroes at the present-day, no A. beccarii and few Cibicides lobatulus. Significantly cooler water conditions are indicated.

Samples 4, 6 and 7, between 0.65 and 0.70m above the Chalk are all (not unexpectedly) very similar. All contain over 80% of E. hannai, several percent of Elphidium pseudolessonii (like the basal sample 1) and a few percent of A. beccarii, and E. frigidum. They also contain the intertidal

Dobbs Plantation Section

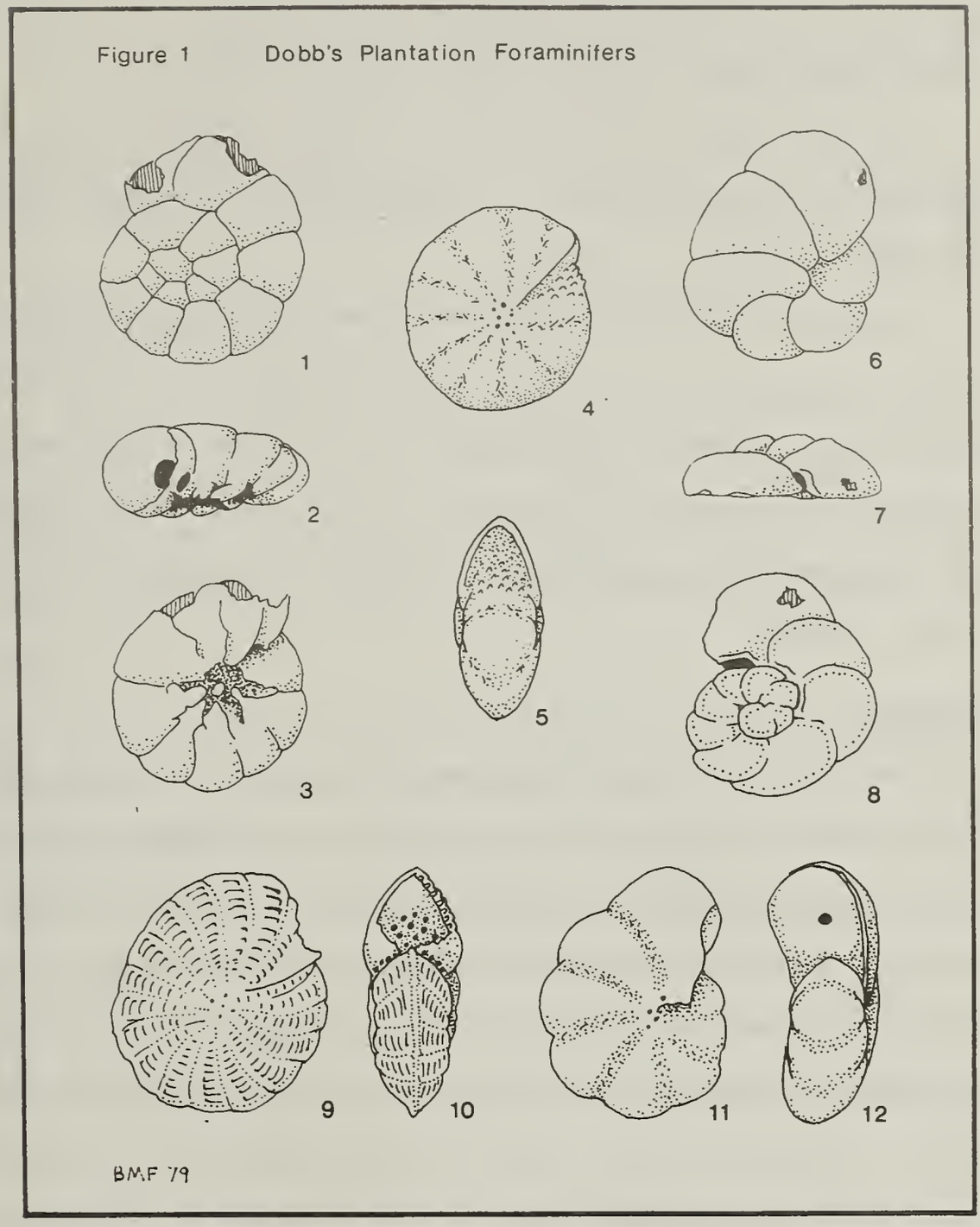

Figure 1. Dobb's Plantation Foraminifers.

1-3 Ammonia beccarii, 4-5 Elphidiella hannai,
6-8 Cibicides lobatulus, 9-10 Elphidium pseudolessonii,
11-12 Elphidium frigidum.

(All specimens are about 0.5mm in diameter; drawn from actual specimens obtained from Dobb's Plantation; all except E. frigidum from sample 1, E. frigidum from sample 2.)

species Elphidium williamsoni. Apart from the presence of this last-named species and the consistently high percentage of E. hannai these samples look rather like a mixture of samples 1 and 2.

Finally sample 8, 1.25m above the Chalk, contains 94% E. hannai accompanied by C. lobatulus, E. pseudolessonii, and single examples of six other species.

Briefly this sequence of foraminiferal assemblages looks like an intertidal or shallow sub-tidal, temperate, open coast assemblage at the bottom, and a boreal, increasingly cold intertidal or shallow sub-tidal assemblage from 0.40 to 1.25m above the Chalk. Re-worked temperate specimens may well contribute to the higher assemblages particularly at 0.65 to 0.70m.

Molluscs

The molluscan faunas throughout the section (Cambridge 1978b) consistently include intertidal species. Two of these, Mytilus edulis and Littorina littorea are commonly considered rocky shore species, but in fact are quite at home at the present day on stable muddy or sandy shores with scattered stones,as well as on exposed chalk or flint. Both environments could be expected in the vicinity of the accumulating Crag at Dobb's Plantation. The infaunal intertidal species at Dobb's Plantation, found at the present day on sandy shores containing variable quantities of mud are Cerastoderma edule, Mya arenaria and Scrobicularia plana. Macoma balthica is present in the top sample only.

Sublittoral species are also present. Forms such as Hiatella arctica and Venus fasciata, which frequent sublittoral shell gravels, are commonest in the lower part of the section, (0.10-0.65m), where the section is indeed more shelly. The sublittoral muddy sand inhabitant

Dobb's Plantation Section

Astarte (Tridonta) montagui occurs in all except the highest sample, but is only accompanied by other sublittoral muddy sand species, Phacoides (Lucinoma) borealis, Nucula nucleus and Turritella communis in the middle (0.65-0.70m) of the section. The sublittoral silt-tolerant Arctica islandica occurs throughout. The sublittoral boreal species Neptunea antiqua occurs only in the highest (1.25m) sample, and the sublittoral motile form Chlamys opercularis occurs only in the lowest (0.10m) sample.

Overall, allowing for the relative total numbers obtained from each sample (sample 2 is the least rich) and the probabl persistence of more robust species (e.g. A. montagui) furthest from source, the general succession of facies at Dobb's Plantation, based on the molluscs found, is:

(a) immediately post-transgressive deposit incorporating intertidal, sublittoral and remanié fossils, with shell-gravel concentrates, areas of bare Chalk and overall evidence of tendency to removal of finer sediment fraction both from accumulating sediment and possibly also from offshore zone. (Samples 1 & 2, 0.10 to 0.40m). It is inferred that the water was shallow and wave and current action effective.

(b) about half-way up the section at around sample 4 (0.65m) there is an influx of sublittoral muddy sand species, which might be taken to be an indication of deepening water, either locally or offshore, but this level also includes some large relatively unworn flints, so this could be simply an indication of increasing storminess bringing in both offshore shells and seaweed holdfasts.

(c) the upper part of the section (0.70m upwards) is characterised by loss of the shell gravel species, dominance of sands with shells and

some medium gravel, and finally introduction of Macoma balthica and the boreal species Neptunea antiqua.

Comparison with Bramerton and Wroxham sections

Only mollusc listings are available from Wroxham for comparison; both foraminifers and molluscs have been investigated from Bramerton (for details see Funnell, Norton & West 1979).

At Wroxham Hall pit (TG 272160) a sample from 0.38-0.61m above the Chalk contained: Mytilus edulis, Macoma sp., Mya arenaria, Hiatella arctica and Yoldia sp., all of which are common throughout the Dobb's Plantation section (although most of the H. arctica found there did not occur more than 0.65m above the Chalk). A sandy and perhaps rocky inter-tidal zone, together with a silty, muddy and possibly shell gravel or stony sub-littoral, are indicated.

At 1.30-1.50m the Wroxham deposit includes: Cerastoderma edule, Macoma sp., Corbula gibba, Donax vittatus, Macoma obliqua and Mya arenaria. Again all of these are present throughout the Dobb's Plantation section and the environmental indications are little changed from those of the lower Wroxham sample.

No Macoma balthica was found at Wroxham Hall. All in all it seems unlikely that there is any significant difference between the Wroxham Hall and Dobb's Plantation mollusc assemblages except that the number of shells collected at Dobb's Plantation was larger.

Comparisons with the Bramerton sections are more complicated. The newly identified Alnus- Quercus- Carpinus pollen assemblage bio zone constituting the BRAMERTONIAN stage extends from the base of the Blake's Pit section to 4.00m above the Chalk. The most abundant molluscs in this stage in Blake's pit are: Abra alba, followed by Mytilus edulis, Cerastoderma edule, Littorina littorea, Calyptraea chinensis, Hiatella arctica, Macoma praetenuis, Macoma sp., Spisula sp. and Yoldia sp.

Dobb's Plantation Section

Apart from the abundance of Abra alba and the presence of Calyptraea chinensis these are all species found in the Dobb's Plantation section.

In the correlative levels in the Bramerton Common section, up to at least 3.10m above the Chalk on the basis of the foraminifers, the molluscs are again dominated by Abra alba in the lower part of the sequence, followed by Calyptraea chinensis, Hydrobia ulvae, Mytilus edulis, Littorina littorea and Hiatella arctica. In the upper part of the sequence Hydrobia ulvae dominates followed by Cerastoderma edule, Macoma sp., Littorina littorea, Nucella lapillus and Cylichna alba. There is more evidence here of sub-littoral and perhaps brackish water forms than in either the adjacent Blake's pit section or the Dobb's Plantation section.

As regards foraminifers the sample from the Bramertonian of the Blake's Pit section contains Elphidiella hannai (47%), Ammonia beccarii (14%), Elphidium pseudolessonii (11%) and lesser percentages of Cibicides lobatulus, Cibicides pseudoungerianus and Cibicides subhaidingerii . The 0.10m above the Chalk level at Bramerton Common is very similar containing the same species in almost indentical rank order of abundance. In both cases the species of Cibicides other than C. lobatulus may be derived. Samples from 0.05 and 1.60m above the Chalk at Bramerton Common are less prolific but still contain E. hannai, A. beccarii, E. pseudolessonii and C. lobatulus as consistent components. All these Bramerton samples are very similar to the lowest Dobb's Plantation sample, which again contains E. hannai (55%), followed by A. beccarii, E. pseudolessonii and C. lobatulus.

The Pinus-Ericales-Gramineae pollen assemblage bio zone, which is thoug to represent the Pre-Pastonian a stage, is found at Blake's Pit, Bramerton at 5.30m above the Chalk. At 4.95 to 5.00m,above the Chalk the molluscs consist of Hydrobia ulvae (63%) followed by Cerastoderma edule,Macoma sp.,

Littorina littorea, Nucella lapillus and Valvata piscinalis. There is little to distinguish this from the molluscan assemblage found at 2.50m above the Chalk in the Bramerton Common section.

However the foraminifers at 4.95 to 5.00m in the Blake's Pit section show E. hannai (56%) and E. pseudolessonii (20%) dominating the fauna with reduced representation of A. beccarii and C. lobatulus and significant representation of Elphidium frigidum such as characterises the 4.60 to 6.10m levels on Bramerton Common. Elphidium orbiculare is also present.

The molluscs at a comparable level, actually at 6.50m above the Chalk on Bramerton Common (ie. at the base of the upper shell bed there) include Macoma sp., Cerastoderma edule, Macoma calcarea, Macoma obliqua, Macoma obliqua, Macoma praetenius, Mya arenaria, Spisula subtruncata. Hiatella arctica, Mytilus edulis and other species.

Both the foraminifers (at 4.95 to 5.00m Blake's and at 4.60 to 6.10m Bramerton Common) and the molluscs (mainly at 6.50m Bramerton Common) show considerable similarity to the Dobb's Plantation samples at 0.65 to 0.70m above the Chalk. This is also probably the most likely level at Dobb's Plantation to which both the Wroxham Hall samples relate. Tentatively therefore it seems likely that the higher part of Blake's Pit (above 4.95m), the middle part of Bramerton Common Pit (4.60 to 6.50m at least), the middle part of Dobb's Plantation (around 0.65 - 0.70m) and possibly all the Wroxham Hall locality (0.38-1.50m) fall in the earlier part of the pre-Pastonian a stage.

The highest level at Dobb's Plantation (1.25m above the Chalk) shows a mollusc fauna in which Arctica islandica, Cerastoderma edule, Mya arenaria, Mytilus edulis, and Littorina littorea continue to be important but are now joined by Macoma balthica. The foraminifers at this level are totally dominated by Elphidiella hannai (94%), the only other species present being

C. lobatulus, E. pseudolessonii, E. frigidum, E. orbiculare and a few others, some of which may be derived. A very similar picture emerges at 10.60m above the Chalk at Bramerton Common where there are no molluscs, but the foraminifers comprise E. hannai (90%), E. pseudolessonii, C. lobatulus, E. frigidum and a few other species including Quinqueloculina seminulum Buccella frigida and Buccella inusitata. This Bramerton Common sample is in its turn very similar to samples taken from the Weybourne Crag at 0.05 to 3.00m above the Chalk at Sidestrand (Funnell 1961a,b). These sediments also contain Macoma balthica (Norton 1967), and West (1979) has recently also allocated them to the pre-Pastonian a stage. The introduction of Macoma balthica into the southern North Sea, and the rise of E. hannai to 90% dominance (with A. beccarii absent) seems likely to have occurred a little way into the pre-Pastonian a cold stage.

Conclusion

None of these suggested correlations is surprising. They are very much in line with the conclusions of nineteenth century geologists, such as Harmer, Wood Jnr and Woodward. There does seem to be a transition from warmer to cooler conditions in the Bramerton sections. It does seem that this culminated in the Wroxham area in the introduction of Macoma balthica, and it appears that this level is to be correlated with the Weybourne Crag of the North Norfolk coast. Even the transgression which brought the Weybourne Crag sea over virgin Chalk seems to be reflected in a change from mainly littoral to sublittoral (Macoma-dominated) conditions in the Bramerton sections. The interesting thing is that the quantitative re-study of molluscs and the quantitative and microscopic study of foraminifers and pollen (both methods largely unavailable to the nineteenth century geologist), combine together to confirm earlier workers' conclusions.

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PRELIMINARY HOLOCENE STRATIGRAPHY OF BRANCASTER MARSHES

P. MURPHY* AND B. M. FUNNELL+

Introduction

Although the accretional coastal environment of North Norfolk has long since been the subject of study by naturalists and physical geographers (Steers 1960), no serious attempt ever seems to have been made to determine the stratigraphy of the Holocene intertidal sediment prism. Mainly in the hope of learning something of past conditions seaward of the Roman fort at Brancaster we sank 13 Hiller auger holes in the summer of 1978 and repeated one of these to a depth of 8 m with a Minuteman auger in September 1978. The position of the line of auger holes in relation to the fort at Brancaster is shown in Figure 1. Our interpretation of the section revealed is given in Figure 2.

Samples recovered from the Hiller auger holes have been examined for molluscs, foraminifers and plant macrofossils.

The General Nature of the Sediments

Apart from a reed-bed near the landward end of the section the surface is a late *Aster* marsh at 2.84 to 3.00 m O.D. and is probably at a level between Mean High Water Neaps and Mean High Water Springs. It is underlain by less than 0.5 to almost 3.0 m of intertidal MUD. Beneath the reed-bed, in auger holes 2, 3 and 4 *Phragmites* rhizomes are present. In auger holes 8 and 9 either side of the main creek *Hydrobia* (*Peringia*) *ulvae*, *Scrobicularia plana* and *Littorina* sp. were found towards the base of the mud. The mud is underlain by sand in all the auger holes, but a thin peat intervenes between the mud and the sand in holes 5,7 and 8. The mud contains numerous foraminifers.

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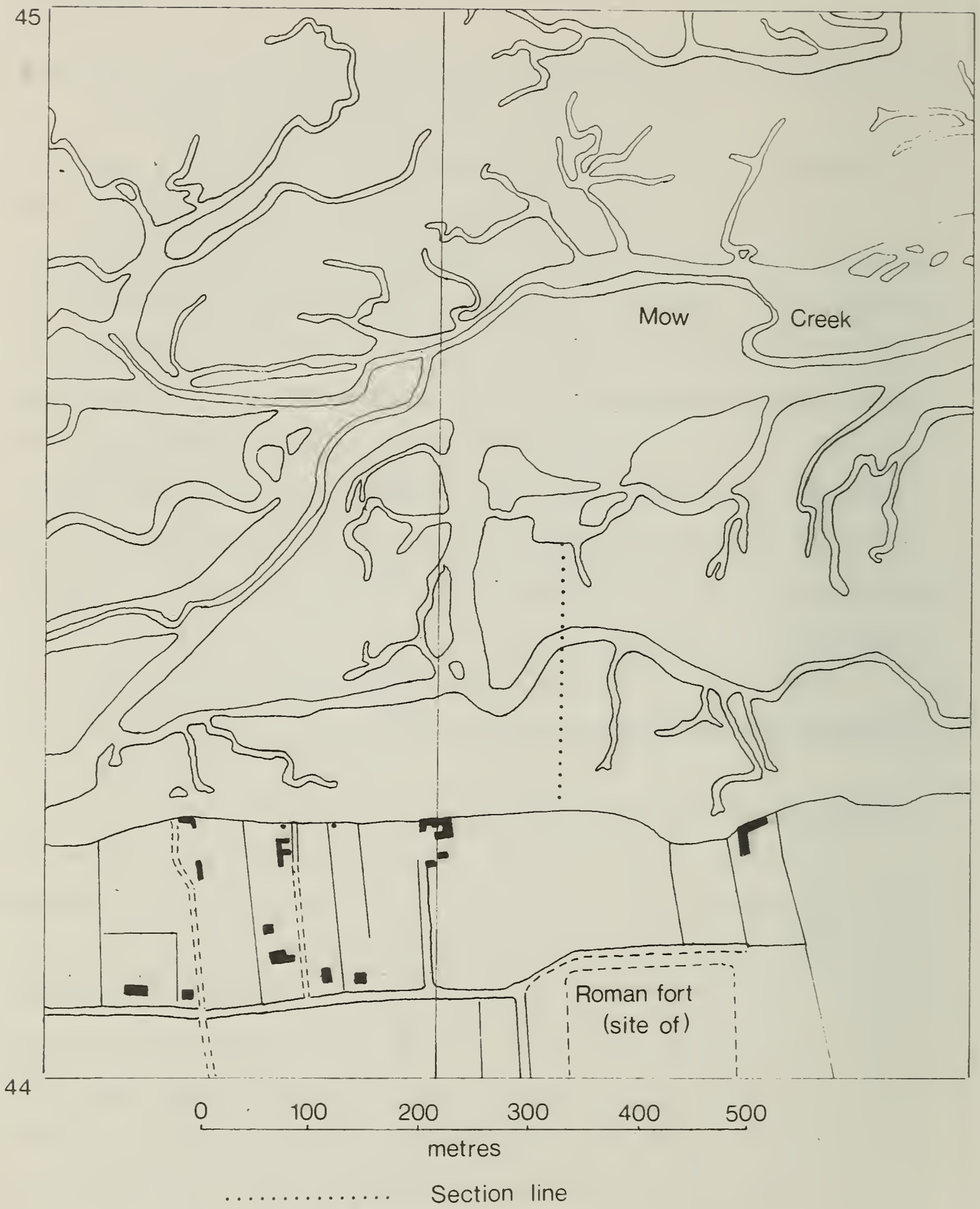

Figure 1 Relation of section through Holocene marsh sediments to position of Roman fort at Brancaster.

The PEAT itself is never more than 0.5 m thick and rests on sand between -0.34 and 0.39 m O.D. It is a brushwood peat and in hole 7 it contained remains of Alnus glutinosa. It is like the Judy Hard peat (Godwin and Godwin 1960, p. 74) in resting on sand but lies at a higher level relative to O.D. (-0.25 to 0.75 m O.D. compared with -3.00 to -0.40 m). Nevertheless it could still be of the same or slightly later age. The Judy Hard peat covers the transition from Boreal to early Atlantic. The later Harbour Channel, Lower Golf Club and Upper Golf Club peats (Godwin and Godwin ibid.) either rest on intertidal clays, or, in the case of the last-named, if resting on sand are covered by dune sand.

The SAND, on which the peats or muds rest, and which are impenetrable with the Hiller auger, are interpreted by us as being of two types. The first, we speculate, underlies the mud of holes 9 to 13. It appears to us that this sand is likely to be part of a small spit or barrier beach rolled shorewards possibly over pre-existing peat and intertidal mud. It is partly the form of the top surface of the sand which suggests this to us. It lies roughly between 0.50 and 2.50 m O.D. Also a sample of sand obtained from the bottom of auger hole 9 contained Ostrea edulis and Cerastoderma sp., both common on the spit and bar sands locally, and yielded specimens of the foraminifers Ammonia beccarii and Elphidium williamsoni which are characteristic of the open coast. The sand in which the auger holes terminated landward we interpret differently. In places it is overlain by peat (in holes 5, 7 and 8) and its surface declines regularly at 1 in 6, from 2.75 m landward to -0.25 m O.D. seaward at hole 8. This could be a beach profile, but if the peat overlying it is of early Atlantic age it would pre-date the local Flandrian transgression, a Holocene marine origin would be ruled out and a soliflucted periglacial or glacial origin could be possible. This sand is over 5 m thick

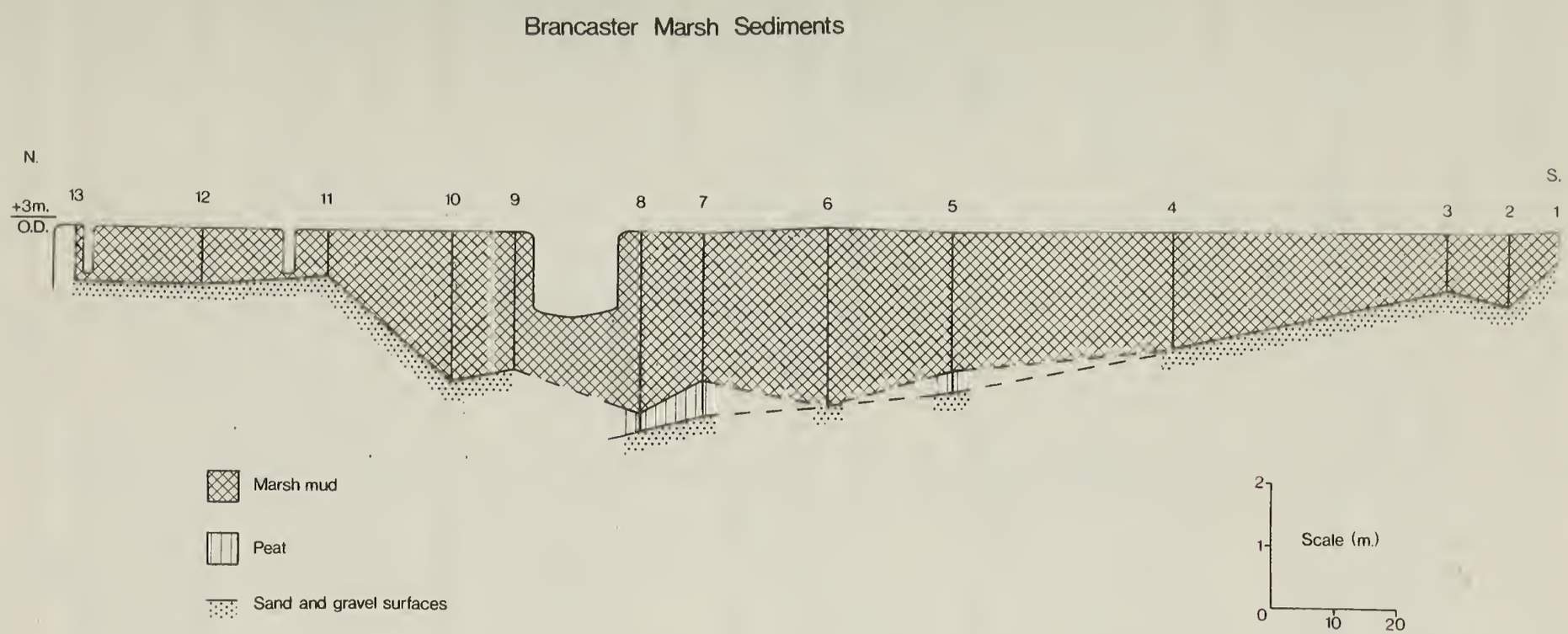

Figure 2 Section through Brancaster marsh sediments

at hole 5, where the Minuteman auger appears to have just reached CHALK at 8 m below surface. Erosion of chalk to -5 m O.D. at this point seems unlikely to have been achieved by marine erosion during the Holocene, but could have been achieved by marine erosion during the Last Interglacial (Ipswichian) - see General Conclusions.

Foraminifera

Arenaceous salt marsh foraminifers were found throughout the intertidal mud of auger holes 5 and 12. Two species dominate the assemblages present, and earlier hopes of estimating past tidal levels from the composition of the assemblages have not been realised during this preliminary investigation. The two species mainly represented are *Trochammina inflata* and *Jadammina macrescens*. *Jadammina* is more common at depth in the mud, *Trochammina* in the upper part (see Table 1). The ratio probably changes with tidal level but no significant changes in sea-level can however be inferred during the period of mud accumulation.

Table 1: Foraminifera from Holocene mud

	Hole No.			
Depth in cm	12		5	
	Total No.	% *Trochammina*	Total No.	% *Trochammina*
0 - 30	250	48	84*	90
30 - 60	122	79	22	91
60 - 90	172	13	21	71
90 - 120	-	-	9	89
120 - 150	-	-	46	30
150 - 180	-	-	44	16
180 - 210	-	-	-	-
210 - 220	-	-	9	11

* *Elphidium williamsoni* and *Ammonia* sp. also present.

General Conclusions

The striking feature of the sedimentary profile obtained seaward of the Roman fort is that it does not indicate any great depth of water before the marsh muds accumulated. At their maximum they only extend down to c. 0.0 m O.D. (i.e. about 0.3 m below mean tide level), and often their base is much higher than this. Immediately north of the fort,peat and sand would have been exposed on the shore between tides before the mud began to accumulate, and the water would only have been 3.0 m deep at MHWS, say 1.8 m deep at MHWN. Deeper water could have existed further seaward (beyond auger hole 8) prior to the emplacement of the sand bank inferred beneath holes 9 to 13.

If the interpretation of the sand surface beneath the mud and peat from hole 1 to 8 as possibly soliflucted and certainly not of marine origin is correct, it could imply that active wave erosion has never occurred at the landward edge of the marsh during the Holocene. The cutting of the old cliff-line which is observed along this coast would then have to be a Last Interglacial (Ipswichian) phenomenon, which might account for its degraded appearance, if it has survived the periglacial conditions of the Last Glaciation.

Acknowledgements

We are grateful to the National Trust for permission to carry out augering on Brancaster marshes, to John Gater for assisting with the Hiller augering, to Derek Edwards for levelling the section, and to Laurie Cartwright for assisting with the Minuteman augering.

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AGE AND CORRELATION OF PLEISTOCENE DEPOSITS IN WEST NORFOLK

ALLAN STRAW *

Abstract

Previous workers have described two types of older glacial till in west Norfolk, differentiated in composition and colour, and by the nature of their contacts in section. Gallois (1978) showed that at low levels the tills survive along valley lines. This situation is compared with that in south-west Lincolnshire, west of the Fens. Further comparison with central and east Lincolnshire situations supports a case that the two tills were emplaced contemporaneously by two confluent ice sheets. A Wolstonian age for the tills is argued on several grounds, and the former correlation of the darker 'Jurassic' till of west Norfolk with the Anglian Lowestoft Till is rebutted. Various non-glacial Pleistocene deposits, including the Nar Valley Beds, are examined as probable Ipswichian or Early Devensian sediments, together with implications regarding sea-levels about the close of the Ipswichian stage.

Introduction

In terms of the glacial history of East Anglia, the tills of west Norfolk have always had a significance beyond the region itself, at least since Baden-Powell's paper in 1948. This arises mainly from the occurrence of a Chalky-Jurassic till which because of its colour and lithology has usually been correlated with the Lowestoft Till of eastern East Anglia. This particular correlation has raised such difficulties in Pleistocene stratigraphy that Gallois, in his recent Presidential Address (1978) was no doubt wise to avoid it, and his criticism of the British Standard Stages (Mitchell et al, 1973) would seem to be well founded. This paper comments on Gallois' interesting survey of west Norfolk, and discusses problems concerning the age and extra-regional relationships of the tills and associated deposits.

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Character of the tills

Gallois described a dark Chalky-Jurassic till in some detail, stressed the Cretaceous and Upper Jurassic components and argued for derivation from the north-west, specifically the central vale of Lincolnshire. He noted also a paler, grey calcareous till rich in chalk and flint erratics though he did not suggest for this any direction of ice movement. Both tills have been exposed in the sand quarries at Bawsey (TF 679193) for many years and were examined by the author in the early 1960s. In a number of places the dark till consisted primarily of disordered Upper Jurassic clay though many large undigested masses of Kimmeridge Clay up to 2m across were seen, still retaining their original bedding. Some chalk and sandstone fragments, nodular flints and Jurassic limestones comprised other erratics. The intensely chalky till, of a light olive-brown colour, contained not only boulders of chalk but also many'milled-out' inclusions forming irregular lenses, and much fresh dark grey flint. Rare erratics included small dolerite, sandstone, limestone and quartzite pebbles. Generally the dark Jurassic till rested sharply though in places irregularly on the Sandringham Sands, with the chalky till superincumbent but not forming a continuous cover. In numerous sections the two tills were intermixed, usually in the manner of irregular lenses and inclusions of the Jurassic till in the base of the chalky till. In places, small masses of chalky material occurred in the Jurassic till, but these could have been crushed and sheared erratics of chalk rather than till inclusions. Everywhere the actual contacts between the two tills were sharp and unweathered, suggesting they had been deposited contemporaneously even though the parent ice masses had crossed rather different outcrops. The composite till mass reached a maximum thickness of over 8m, but was restricted to the eastern half of the Bawsey quarry, lying in a broad hollow that appeared to trend north-north-west across the Bawsey spur.

Both tills have been described in greater detail by Evans (1975). He too noted sharp and irregular contacts, and showed by particle-size analysis that in spite of the frequency of Kimmeridge Clay inclusions, the Jurassic till had a high sand content. This was no doubt acquired from the underlying Sandringham Sands. Evans concluded that the upper chalky till was emplaced during a readvance phase across a stagnating lower till, though both belonged to the same glacial phase. Gallois however stated that many sections elsewhere in west Norfolk showed gradational contacts, and the lower, Jurassic till merely represented a basal layer of slow-moving ice.

Distribution of the tills

It is clear from Gallois' sketch-map (1978, Fig. 1) and from the Old Series Geological Survey maps that the tills are now preserved either on the higher ground of spur crests and hill summits or along the main valleys where the thickest sequences exist. The thinness of the tills on the higher ground and general absence on slopes is a consequence largely of Devensian periglaciation, and 'head' or solifluction loams and gravels of variable lithology and thickness occur widely in west Norfolk. Such 'head' frequently includes till material and has seemingly been misinterpreted as till in a number of earlier publications (West and Donner, 1956; Stevens, 1959; Woodland, 1970).

Of great interest are Gallois' demonstration that tills occupy the floors of the main valleys and his suggestion that the buried valleys represent parts of a pre-glacial river system. Such a situation is not unique, for it recurs west of the Fen basin in Kesteven. Recent work here (Wyatt, 1971; Wyatt et al, 1979; Rice, 1965; Harrod, 1972) has confirmed that systems of west-east valleys excavated in Middle Jurassic rocks are in several instances completely filled with glacial materials. However in Kesteven it is probable that certain north-south valleys, particularly part of the River Witham valley north and south of Grantham and others just south of the scarp crest south-west of Grantham are in

large part glacially rather than fluvially or glacifluvially eroded (Straw, 1969).

It is difficult to accept all the west Norfolk buried valleys as of fluvial origin, even though Gallois argues strongly against a sub-glacial origin. It seems however from his paper that he is considering sub-glacial excavation by meltwaters in the manner of tunnel valleys' (Woodland, 1970) and not direct erosion by glacier ice, although the final two points of those he lists for a fluvial origin in fact testify to such erosion. The west Norfolk tills on all accounts consist largely of locally-derived materials; the Kimmeridge Clay inclusions, Carstone fragments and the high sand content of the Jurassic till, and great quantities of fresh chalk and flint in the upper till, all point to considerable erosion by ice. Indeed the Bawsey tills may well rest in a glacially eroded groove. On a wider scale, the high proportion of Upper Jurassic clay in tills south of the Fens testifies to significant erosion of the central vale of Lincolnshire and the northern Fen basin (Straw, 1958, 1979) and the anomalous size of the Wash gap must owe something to the passage southward of glacier ice. It may well be therefore that, as in Kesteven and at Welton-le-Wold in Lincolnshire (Alabaster and Straw, 1976), pre-glacial valleys orientated generally transverse to ice movement gained thick infills of till, but the gradient of some existing valleys may have been reversed, and other linear depressions some over-deepened may actually have been produced, by the ice itself. Gallois' tentative reconstruction of a former river system does not therefore seem firmly based, for although pre-glacial valleys within the Upper and Lower Cretaceous outcrops obviously survived glacial erosion, those over Upper Jurassic rocks, like those over the Lower Jurassic rocks of the Vale of Belvoir (Straw, 1963; Rice, 1968) probably did not. Depressions on the Fen basin floor revealed by borehole logs would then have been glacially eroded.

Wider field relationships and circumstances of deposition

Although Evans (1975) made no attempt at extra-regional comparison of the tills, Gallois (1978) did relate the Jurassic till of west Norfolk firmly to that of central Lincolnshire (the Wragby Till - Straw, 1969) and with similar tills beneath the Fens, but he did not trace the upper chalky till further afield. However it is not possible to understand fully either the circumstance of deposition of the West Norfolk tills or their significance in broader chronostratigraphic terms unless recourse is made to wider field relationships and this limitation is apparent in both Evans' suggestion of a readvance of ice to account for the upper chalky till and Gallois' view that a single slow-moving ice sheet was responsible for both tills.

The upper chalky till at Bawsey is identical in lithology to chalky tills over the Chalk outcrop of west, central and north Norfolk (Straw, 1965). These latter tills (collectively the Marly Drift), also dissected and affected greatly by later periglacial processes, contain far-travelled erratics and marine materials, for example the large quantities of wave-eroded flint cobbles and pebbles eastward of Docking, which provide ample proof of ice movement from the north down the east coast and not from central Lincolnshire to the north-west.

The lower Jurassic till of west Norfolk is an extension of the Wragby Till of Lincolnshire which was produced by ice streaming south-south-east parallel to the Cretaceous escarpment. However at this stage the Lincolnshire Wolds were also covered by ice, some of which crossed the central Wolds southward into the Bain valley (Straw, 1966) while more crossed the southern Wolds into the Wash area. Near the Bain valley, the Wold ice, laying down a highly chalky till (Calcethorpe Till), abutted the central Lincolnshire ice so that now, in a narrow zone from Hainton (TF 180845) to Kirkby-on-Bain (TF 242623) the Calcethorpe Till directly overlies the highly Kimmeridgian Wragby Till. The Wold ice was deflected

south-south-east by the central Lincolnshire ice, but the line of junction (not necessarily vertical) between the two may well have fluctuated a little west and east.

This situation is instructive with respect to the west Norfolk tills. The Jurassic till was also emplaced by ice moving parallel to the Chalk scarp (i.e. from the north-north-west) across the pre-glacial valleys and interfluves of the Lower Cretaceous outcrop, eroding some Upper Jurassic clay and Lower Cretaceous sandstone. At the same time, ice moving generally down the east coast crossed the Wash into west and north Norfolk. This North Sea ice of course effectively stopped the inland Lincolnshire ice from flowing eastward into north Norfolk, and although deflected somewhat to flow a little east of south as in the Bain valley, it may have been sufficiently powerful partly to override the inland ice and partly to displace the zone of contact a little westward of the Chalk escarpment. This situation not only accounts satisfactorily for the stratigraphic and structural relationships of the west Norfolk tills, but it demonstrates conclusively the essential contemporaneity of the North Sea and inland ice masses, and of the Marly Drift and the Wragby Till. There is clearly no requirement for a readvance to account for the upper chalky till, and two contiguous and partly overlapping ice sheets, probably moving fairly quickly in view of the basal erosion, would seem to provide a better explanation for the two highly-contrasted yet intimately-related tills than a single ice-sheet.

Age of the tills

Gallois notes that the only till younger than the west Norfolk tills is the Hunstanton Till which reaches no further south than Wolferton (TF 658286) and which is widely accepted as Devensian. The composition and disposition of the Hunstanton Till and its association with glacifluvial features such as eskers and meltwater channels separate it clearly from the weathered and dissected Marly Drift and the west Norfolk tills (Straw, 1960). In terms of the British Standard Stages the latter should therefore

be referable to either the Anglian or the Wolstonian glacial stages. If to the former, then the time gap between the west Norfolk tills and the Hunstanton Till included the Hoxnian and Ipswichian interglacials as well as the Wolstonian, if to the latter, then only the Ipswichian interglacial intervened.

Most workers have considered the west Norfolk tills to be Anglian though, as far as the author can detect, for no firm reason. Baden-Powell (1948) described the west Norfolk tills as Lowestoft-type, and West and Donner (1956) accepted his view that they were emplaced during the Lowestoft Glaciation. Stevens (1959) also accepted without question the correlation of the Jurassic till beneath the Nar Valley Beds with the Lowestoft Glaciation, and this seems to have conditioned a correlation of the Nar Valley Beds with the Hoxnian. More recently Evans (1975) reversed the argument and tentatively regarded the west Norfolk tills as Anglian because in places they appeared to be overlain by the Nar Valley Beds! Shotton et al (1977) concurred with this opinion, and admitted evidence for one major lithological unit of chalky till over East Anglia (Perrin et al, 1973) even though they appreciated the difficulties of correlation that arose between deposits east and west of the Fens. So constrained, rather than for any argued reason, they placed the Wragby Till of Lincolnshire also in the Anglian. Gallois (1978) remained non-committal on age, but confirmed the continuity of the Wragby Till beneath the Fens with the west Norfolk Jurassic till and also the contemporaneity of both the west Norfolk tills.

The argument for a single complex of chalky tills over East Anglia is not however overwhelming. In the first instance, an apparent absence of examples of superimposition of chalky tills of different ages should not be surprising. During each glaciation of eastern England, ice-sheets have destroyed most of the drifts and soils in their tracks (Wymer and Straw, 1977) and just as the Devensian tills of northern England rest

directly on bedrock so do both Wolstonian and Anglian chalky tills, the latter surviving only outside the range of Wolstonian ice. Secondly it is being increasingly recognized that if successive ice-sheets traverse identical outcrops then closely similar tills, yielding closely similar heavy mineral assemblages for example, may result (Wymer and Straw, 1977; Shotton et al, 1977; Gallois, 1978). The essential point is that the Jurassic till of west Norfolk does not have to be correlated with Lowestoft Till merely because of its lithological similarity. In fact lithological similarity should not be pressed too far, because while the west Norfolk till contains much Lower Cretaceous material and virtually no Triassic indicating ice flow from the north-north-west, the Lowestoft Till contains little Lower Cretaceous but noticeable quantities of Triassic, including recognizable lumps of Keuper Marl, and some Carboniferous, confirming ice flow from the west-north-west.

Against this majority view, Straw (1960, 1965, 1969, 1973, 1979) has argued consistently that the chalky tills of Lincolnshire and of central and north Norfolk are of Wolstonian age. There is no evidence for more than one period of valley incision between the chalky tills and the Devensian tills, the Calcethorpe and Wragby Hills of Lincolnshire are overlain extensively only by Devensian gravels and Flandrian alluvium, the Marly Drift is intimately related to the overlying outwash gravels accepted by, for example, Sparks and West (1972) and Shotton et al (1977) as Wolstonian, and a Wolstonian limit across Norfolk from Weybourne and Aylsham by way of Norwich and Diss to the southern Brecklands can be identified (Straw, 1974, 1979).

Recently, biological evidence has supported a Wolstonian age for the Lincolnshire chalky tills. At Tattershall (TF 207567) Ipswichian interglacial depsoits rest indubitably on Wragby Till (Girling, 1974; Shotton et al, 1977). At Welton-le-Wold (TF 282884) a meagre but probably

Hoxnian mammalian fauna and three Acheulean hand-axes have been recovered from gravels beneath chalky tills (Welton and Calcethorpe Tills) which are demonstrably older than Devensian, and are laterally contiguous with the Wragby Till (Straw, 1966; Alabaster and Straw, 1976). In Norfolk, at Beetley (TF 973187) Ipswichian deposits rest on outwash gravels of the Marly Drift. In fact, nowhere over Lincolnshire, the east Midlands or central and west Norfolk are the chalky tills overlain by fossiliferous sediments of proven Hoxnian or older date. Also it can be noted that wherever valleys have been incised into and through the chalky tills, fluvial terrace sands and gravels within these valleys have without exception been considered of Ipswichian or younger age.

Age of the non-glacial deposits

The arguments presented above point strongly to a Wolstonian rather than an Anglian age for the west Norfolk tills, and it is pertinent therefore to examine briefly the implications of such a designation on three groups of non-glacial deposits in west Norfolk described by Gallois (1978).

Above and probably conformable with the chalky tills are the Nar Valley Beds, succeeded unconformably by the Tottenhill Gravels. In north Norfolk, the Hunstanton raised beach, probably contemporaneous with the upper part of the Tottenhill Gravel lies beneath the Hunstanton Till.

The Hunstanton raised beach has long been ascribed to the Ipswichian interglacial and correlated with the buried beach at Sewerby in east Yorkshire, but there is one feature common to both that is worth comment. The Hunstanton Till and the Holderness tills are believed by many to be Late Devensian (Shotton, 1977; Madgett and Catt, 1978) emplaced after about 18,250 years B.P., but the only deposits between both shingle beaches and the overlying tills are relatively thin periglacial (aeolian and/or soliflual) materials with no observable weathering horizons above or below; meagre accumulations indeed if the beaches are Ipswichian and some 50,000 years elapsed between shingle accretion and till deposition!

However, the Hunstanton Till might be of late Early Devensian date (Straw, 1961, 1979) and if the beaches were formed no earlier than the close of the Ipswichian (or even into the Early Devensian) then this inconsistency is reduced.

Gallois showed the Jurassic till to pass upward through varved clays into the Nar Valley Beds. The latter comprise lower freshwater and upper marine units, and contain a flora and fauna indicative of the climatic sequence of at least the first half of an interglacial period, by which time sea-level had reached about 30 m O.D. The Nar Valley Beds have been generally regarded as Hoxnian since the work of Stevens (1959) though previously Baden-Powell (1934, 1953) for example had claimed the them as Last (Ipswichian) interglacial. Stevens' palynological evidence in itself was not conclusive, substantial differences with the Hoxne pollen diagram were noted, and her dating of the deposit at least as presented in the paper would seem to have relied more heavily on its position above a Lowestoft-type (ipso facto Anglian) till, supported by its height up to at least 24 m O.D. which might be considered to place it outside the Ipswichian range (West, 1972). However, it must be noted that the Nar Valley Beds lie <u>within</u> a valley system, a location generally held characteristic of Ipswichian deposits (Sparks and West, 1972), that the erosion between the lower freshwater unit which terminates toward the end of pollen zone IId and the upper marine unit which commences in zone III (Stevens, 1959) may be compared with the base-level oscillation frequently observed in Ipswichian aggradation deposits (Sparks and West, 1972), and that ostracods in the Nar Valley Beds differ from marine Hoxnian ostracod assemblages in Britain and western Europe (Lord and Robinson, 1978).

Gallois (1978) separated the Tottenhill Gravels into two units, correlated the upper one with the Hunstanton raised beach and demonstrated its unconformable position on the lower unit, on the Nar Valley Beds and on Kimmeridge Clay. This Upper Tottenhill Gravel is a strandline deposit

lying between 3 and 7 m O.D., but the lower gravel unit, also unconformable on the Nar Valley Beds has some characteristics of a channel-fill.

Chronology

It should be apparent that the chronology of the tills and associated deposits of west Norfolk has not been established to date with any degree of certainty.

Gallois merely referred the Nar Valley Beds to a temperate climatic phase following the cold climate witnessed by the chalky and Jurassic tills. He related the Lower Tottenhill Gravel to an early phase of the Hunstanton glaciation, and the Hunstanton raised beach and Upper Tottenhill Gravel to a succeeding warmer period, followed by the Hunstanton glaciation.

The traditional interpretation would place the chalky and Jurassic tills in the Anglian and the Nar Valley Beds in the Hoxnian. If the Hunstanton Till is Devensian and the Hunstanton raised beach Ipswichian then the Lower Tottenhill Gravel would conveniently represent the Wolstonian.

However, a case has been argued above for regarding the chalky tills of west Norfolk as Wolstonian, the corollary of course is that the Nar Valley Beds were aggraded in the first half of the Ipswichian. If the Hunstanton glaciation took place in the late Early Devensian, then the Lower Tottenhill Gravel and the Hunstanton raised beach/Upper Tottenhill Gravel can be referred to the late Ipswichian and Early Devensian respectively.

The Hunstanton raised beach and Upper Tottenhill Gravel would testify to a sea-level a little higher than present in the early Early Devensian, whereas the older Lower Tottenhill Gravel suggests some channelling of the Nar Valley Beds when sea-level was rather below present. Apart from the probability that the Lower Tottenhill Gravel represents a short-lived even catastrophic event, too little detail is known of the manner of recession of sea-level from an Ipswichian 'high' to deny the possibility of oscillatory movements over a period of perhaps some tens of thousands of years.

The point of this latter discussion is not so much to prove a particular chronological succession as to demonstrate that the timing of events recorded in the deposits and features described by Gallois and others in west Norfolk is capable of a different and in the author's view equally valid interpretation from that which has prevailed to date. The broader purpose of the paper has been to show that the age of the chalky tills of west Norfolk is very probably Wolstonian and not Anglian, that as a consequence the Nar Valley Beds deserve serious and independent re-assessment, and that relative land/sea movements during the late Ipswichian in eastern England were more complex than has so far been demonstrated.

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A FROST CRACK SYSTEM AT COVEHITHE CLIFF, SUFFOLK

R.G. WEST*

The cliff at Covehithe (G.R. TM 529820) has in the last few years been subject to rapid erosion. In March 1978 the cliff sections so exposed revealed a system of frost cracks penetrating the sands and gravels of the Westleton Beds (Hey 1967). Eight such cracks were seen. Their disposition in relation to the road ending at Covehithe Cliff is shown in Figure 1, which also sketches the stratigraphy at each frost crack site. The cliff section is composed of a number of sedimentary units (see section in Figure 48, West 1980). At the base are the laminated clays of the Baventian stage, which often form a ledge to seaward of the cliff. These have been described recently by West, Funnell and Norton (1979). A thin bed of red loamy sand, up to 60 cm thick and shelly in places, overlies the Baventian clays unconformably. This sand is overlain by up to 3.5 m of intertidal laminated beds of clay, silt and sand, showing bioturbation. The Westleton Beds sands and gravels, up to 5 m thick, lie unconformably on these intertidal sediments. Above them, thickening south of the road, is a series of sands with minor associated gravels, up to 5 m thick, with a pebble content described by Hey (1967). This unit is sealed by a reddish loamy sand up to 1.5 m thick and the modern soil.

The upper limits of the cracks, where they widen rapidly to 10-20 cm, lie near the junction of the Westleton Beds and the upper sands and gravels. Most of the cracks are sealed by a thin lag gravel at the base of the upper sands and gravels. The cracks narrow rapidly to a few centimetres wide and carry on down as narrow cracks penetrating the Westleton Beds and in some examples the underlying laminated beds, as indicated in Figure 1.

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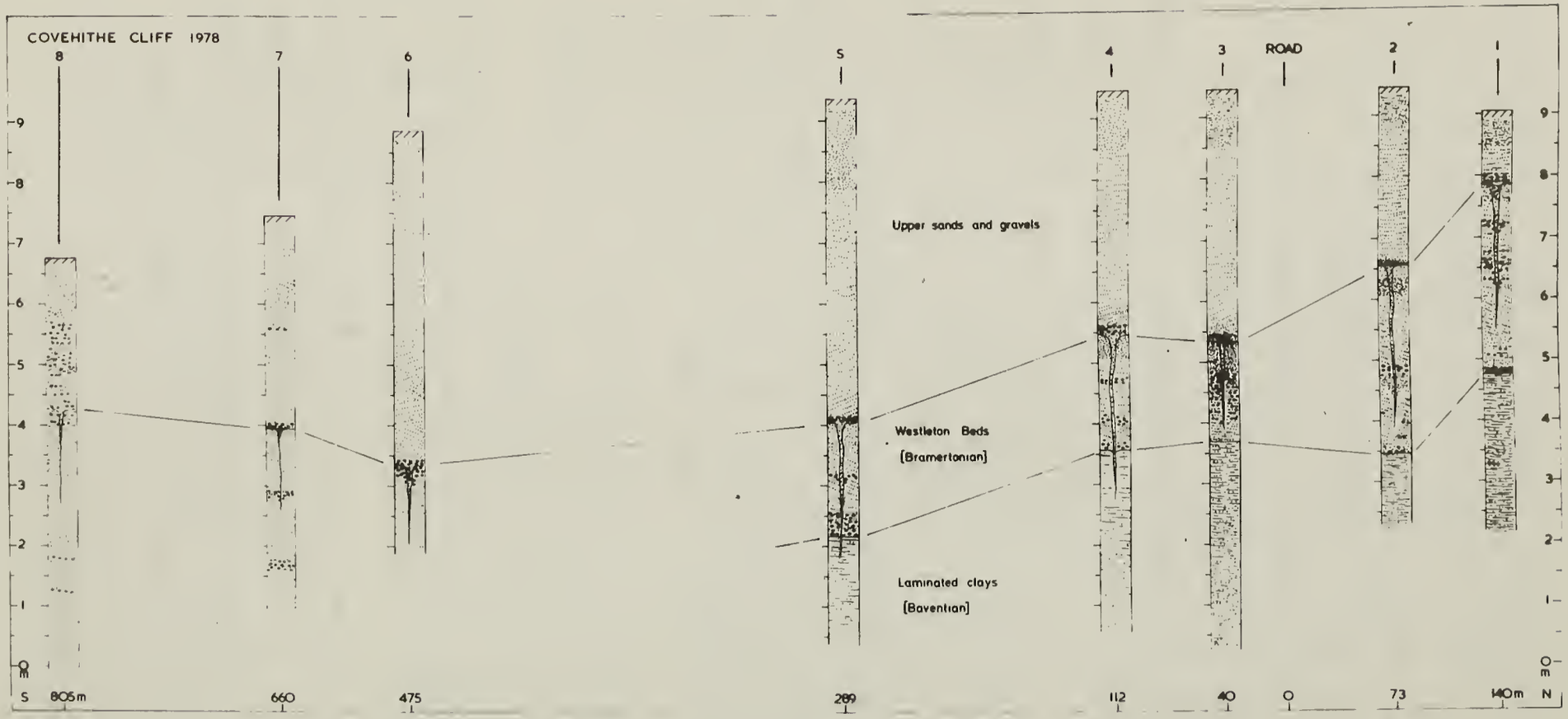

West

Fig. 1. Disposition of frost cracks in Covehithe Cliffs

Frost Cracks at Covehithe Cliff

The cracks are unusual in combining narrowness with a good depth of penetration. The depth of penetration suggests they are not desiccation cracks, but rather thermal contraction cracks associated with freezing of the ground (Washburn 1973). No development of massive ice-wedges or sand-wedges seems to have occurred. The reason may be that the freezing period was short-lived, or that the coarse-grained sediments were incompressible and therefore thermally relatively incontractible or that they were free-draining with a low water content.

The disposition of the cracks indicates the presence of a former land surface on an eroded surface of the marine Westleton Beds. This land surface was subjected to deep freezing. Subsequently the upper sands and gravels aggraded under a fluviatile regime.

The dating of the freezing episode is uncertain in view of the unknown age of the upper sands and gravels. It must be post-Westleton Beds, i.e. post-Bramertonian (Funnell, Norton & West 1979). If the upper sands and gravels are Anglian, their lithology indicates that they pre-date the chalky boulder clay (Lowestoft Till) ice advance, so that the freezing period may be in the earlier part of the Anglian cold stage. It may then correspond to an ice-wedge network seen penetrating Cromerian sediments at Corton (Gardner & West 1975). If the upper sands and gravels are pre-Anglian, then the freezing period must be in a cold stage between the Bramertonian and the Cromerian. Two such cold stages are documented on the Norfolk coast, the Pre-Pastonian and the Beestonian. Ice-wedge casts and a polygon system are known from the Beestonian (West 1968, 1980), but not certainly from the Pre-Pastonian. Further work on the coastal sections of the Covehithe Cliff would probably make a more accurate date possible.

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HISTORY AND PROGNOSIS OF SUBSIDENCE AND SEA-LEVEL CHANGE IN THE LOWER YARE VALLEY, NORFOLK.

B.M. Funnell*

Abstract

A model of subsidence and sea-level change in the lower Yare valley is proposed, based on the levels of successive freshwater and estuarine deposits over the last 8000 years. A projection of relative land-sea changes for the next 2000 years is made on the basis of continuing subsidence at the rate of 1.5m per 1000 years, and continuing sea-level fluctuations of an amplitude of about 1.5m and wavelength of about 1000 years.

Introduction

Many difficulties and uncertainties confront any attempt to elucidate the history of land-sea level changes on the East Anglian coast, but some of the fullest information on which such an attempt can be based is contained in the alluvial stratigraphy of the east coast valleys of the rivers Bure, Yare and Waveney. These were originally studied by Jennings and Lambert in their investigations of the origin of the Broads (Jennings 1952, Lambert and Jennings 1960, see also Ellis 1965), and latterly also by Coles in his investigations of the foraminifers and palaeogeography of the central Broadland during the Holocene period (Coles 1977). Meantime Tooley (1978), working on deposits on the more stable coast of Lancashire, has deduced a useful detailed history of sea-level changes over the last 9000 years. Putting these results together it is now possible to devise a history of subsidence and sea-level change in the lower Yare (Figure 1) that seems to account adequately for the known spatial and temporal extent of freshwater and estuarine deposits in the lower Yare valley

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Previous models

Few previous attempts have been made to interpret the history of land-sea level changes in the vicinity of Great Yarmouth. The earlier interpretations, based mainly on archaeological, but in part also on biological evidence, were intended to help understanding of the history of excavation and subsequent flooding of the Broads (Green and Hutchinson 1960). More recent attempts were made in connection with the engineering evaluation of the Yare valley (flood protection) barrier (Rendel, Palmer & Tritton 1977). Neither of these attempts have proved totally satisfactory. The mainly archaeological and biological evidence from the Yarmouth spit was thought to indicate some large and seemingly inexplicable land-sea level changes in post-Roman times, and the tide-level evidence from the last 70 years, used by the engineers, implied a minimal (+0.3 ± 0.2m per 1000 years) trend that is small by comparison with the changes seen over the last few thousand years.

The basic stratigraphical succession in the Lower Yare valley is:

5. Upper Peat, a reed and brushwood peat deposited after the withdrawal of estuarine conditions.
4. Upper Clay, an estuarine clay deposited 2000 - 1500 BP, its top at about -0.5m O.D.
3. Middle Peat, a brushwood and reed peat deposited 4500-2000 BP across the entire valley.
2. Lower Clay, an estuarine clay deposited 7500-4500 BP, its top at about -5.5 to -6.5m O.D.
1. Lower Peat, a mainly reed peat deposited before 7500 BP.

These beds record the alternation of marine and freshwater conditions in the lower valley and the fluctuation of sea-level in relation to deposition in the valley.

The present model

No attempt is made here to justify fully the model that is presented in this paper, but the chief points used in its construction need to be explained.

First, it is assumed that the curve of sea-level changes elucidated by Tooley (1978) is essentially correct, at least for N.W. Europe. It corresponds rather closely, both in frequency and amplitude, with a similar curve deduced by Mörner for southern Sweden (Mörner 1976).

Secondly it is assumed that we know accurately the present level of the top and feather edge of the Upper Clay which accumulated in Broadland in Roman times (dated by ^{14}C to around 1600 BP (= 400 AD) and occurring now at between -0.50 and -0.70m O.D.). Having deduced from the contained microfaunal evidence that the intertidal clay sedimentation occurred to about MHWS (in present-day terms + 0.50m O.D.) we can infer a simple relative fall of the land in relation to the sea since 1600 BP of at least 1.0m. However, at 1600 BP Tooley records a relatively high sea-level of + 1.75m compared to the present-day. Therefore the total absolute fall of the land, measured by the present level of the top of the 1600 BP estuarine clay relative to the 1600 BP sea-level is from + 2.25 to -0.50m, ie. 2.75, or a subsidence rate of about 1.7m per 1000 years. A similar calculation can be made in relation to the top of the much older and deeper Lower Clay which occurs at depths of between -6.0 and -20.0m O.D. beneath the lower Yare alluvium. Here we can again be quite certain, from microfaunal evidence, that deposition of the estuarine clay ceased in a high salt marsh environment (= MHWS or about + 0.95m*) at about, (and this figure by comparison is very approximate), 4500 BP. If we use a figure for the present-day level of

(*The O.D. level for MHWS given here differs from that used for the Upper Clay because the top of the Upper Clay is observed at the inland end of the lower Yare valley and the top of the Lower Clay is observed at the seaward end.)

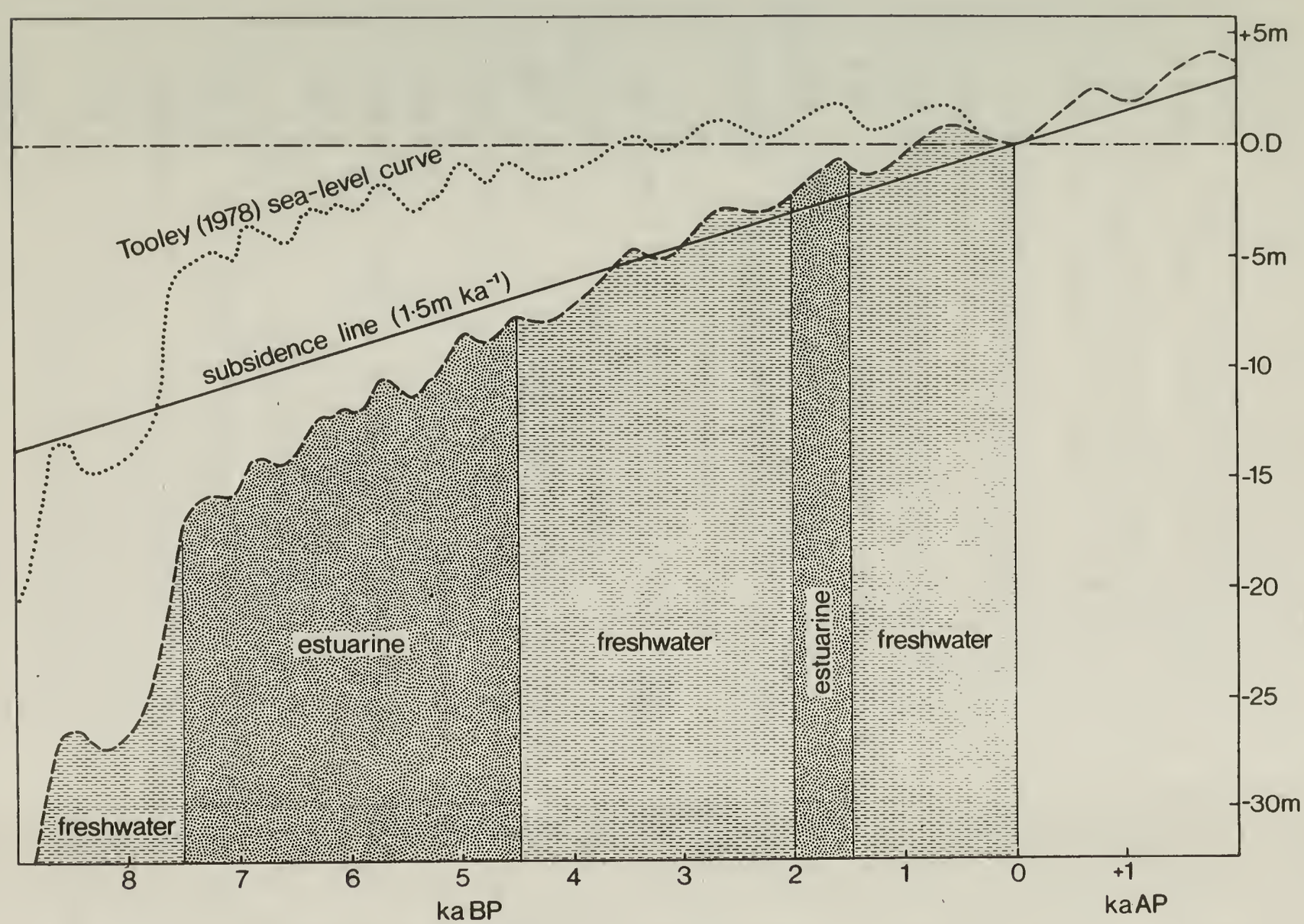

Figure 1. Land-sea level changes in the lower Yare valley 8000 BP (= 6000 BC) to 2000 AP (= 4000 AD). The sea-level curve of Tooley (1978), obtained from a coastal area of no net subsidence or elevation, has been modified to incorporate a continuing rate of subsidence of 1.5 ka^{-1}. The resultant land-sea level curve has been applied to the lower Yare valley and correlated to alternations of freshwater and estuarine conditions in the valley from 8000 BP to the present-day. It is speculatively continued to the year 2000 AP.

the top of this Lower Clay of -6.0m, and add +0.95m to give the total simple fall in level since deposition, we get 6.95m in approximately 4500 years. However Tooley's sea-level curve stands at a minimum of -1.0m below present O.D. at around 4500 BP and levels as low as -1.75m occur not long before and after this date. Therefore the actual subsidence since 4500 BP is less, either 5.95m (6.95 - 1.0m; corresponding to 1.3m per 1000 years) or 5.20m (6.95 - 1.75m; corresponding to 1.2m per 1000 years). There are many uncertainties in making such calculations. The two most important are the uncertainty in the age of the level determined and the vertical variations of that level from place to place. There is also, of course, the uncertainty of the Tooley curve of sea-level change itself. However, if we re-calculate with slightly different but still realistic ages, or slightly different but still realistic levels, or make slightly different tidal level assumptions about the environment of deposition of the critical sediment, most of the answers continue to give a subsidence rate between 1.2 and 1.8m per 1000 years. Figure 1 is therefore basically Tooley's (1978) sea-level curve, actually dotted in on the figure, re-drawn with a subsidence rate of 1.5m per 1000 year added or incorporated. It is also extended 2000 years into the future by continuing the 1.5m per 1000 year subsidence rate and repeating the last two cycles of the Tooley sea-level curve. Alternative ways of extending the Tooley cycles could have been chosen but they would not substantially affect either the amplitude or frequency of the result. Similarly other subsidence-rate lines, especially between 1.2 and

1.8m per 1000 years, could have been chosen, but these too would not have greatly affected the resultant levels. (The choice of a straight subsidence-rate line is of course a simplication, but it is not known to be contradicted by any currently available data).

The most interesting aspect of the land-sea level curve drawn on such a simple basis is that it is consistent with a great deal of what we know about the alluvial history of the Yare valley. Freshwater gives way to estuarine conditions (Lower Clay overlies the Lower Peat) at about 7500 BP and at a present depth of about -20m as the most rapid episode of Holocene post-glacial sea-level rise occurs. At about 4500 BP (-6.0m O.D.) estuarine deposition is replaced by freshwater (Middle Peat overlies Lower Clay) as the rate of sea-level rise slackens off and rapid estuarine deposition overtakes the continuing rate of subsidence. Estuarine conditions return after the deposition of the brushwood peats (Upper Clay rests on Middle Peat), from 2000 BP onwards at depths of about -2.0m, and culminated at 1600 BP at a depth of -0.7m. Freshwater conditions returned (Upper Peat developed in places on top of the Upper Clay) from about 1500 BP (= 500 AD) as the estuarine conditions withdrew at a time of sea-level fall. The sedimentary record fails to record events adequately from this time onwards because of increasing human intervention with drainage, etc. However, we can see the sea-level fall bottoming at about 1300 BP (= 700 AD) would have assisted the mediaeval abstraction of peat whereas the sea-level rise culminating at about 700 BP (= 1300 AD) corresponds with the period of decline of the Broadland peat diggings and their conversion into Broads by flooding.

Lastly, the decline of sea-level since the 14th century and the apparent coincidence of the present-day with a turning point of the Tooley cycle can be seen as a possible reason for the last of short-term evidence for subsidence at the East Anglian coast at the present-day.

Comparison with previous interpretations

Interpretations of land-sea level change in the vicinity of Great Yarmouth were, as mentioned previously, made by Hutchinson and Green on the basis of a variety of archaeological and biological observations for the period from around 1600 to 600 BP (= 400 to 1400 AD). None of these interpretations are exceptional, ie. they can be accommodated within the limits of error by the changes as graphed on Figure 1. All, that is, except the inference of a relative sea-level of -4.0m at around 700 BP, precisely coinciding with the time of the great flood of 1287 AD! That conclusion was reached on the assumption that the barnacle *Balanus balanoides*, and the mollusc *Mytilus edulis* were essentially intertidal organisms, and that their occurrence at depths of c. -5.0m O.D. implied subsequent land subsidence or sea-level rise of 4.0m or so in the intervening 700 years. However, both species do occur sub-tidally in appropriate circumstances and the conclusion drawn regarding relative contemporary land-sea levels is not necessarily valid. No other evidence requires sea-level at Great Yarmouth to have been sensibly different to the present c. + 0.2m O.D. at 700 BP, although the tidal range of the river side of the spit at its proximal end may have been less because of its longer southward extension towards its then opening to the sea near Lowestoft.

Interpretations of recent land-sea level changes in the vicinity of Great Yarmouth made by civil engineering consultants (Rendel, Palmer & Tritton 1977) have relied on the interpretation of tidal-gauge and maximum tidal level records. These show cyclic fluctuations over the 70 or so years for which they are available with no very clearly defined systematic trend either upward or downward. The only comment that can be made here is that this is precisely what would be expected at the present point of conjunction of the subsidence and sea-level curves as expressed on Figure 1.

Fallability of the prognosis

Although Figure 1 has been boldly projected from 8000 BP through the present day to 2000 AP (= c.4000 AD) it must be clearly understood that this is not necessarily what is going to happen. It just looks like the most likely outcome if trends identified in the past record continue into the future. The Tooley sea-level curve could be about to change its character at the present time, just as it has, as you can see, in the past. Also the subsidence line could be about to change either its rate (= quantity) or its direction (=sign). Subsidence has apparently been the rule in the Post-Glacial epoch on the east coast of East Anglia, but it has by no means always been the rule in the last few 100 ka of the Quaternary period. It could reverse itself again. It would of course be possible to refine the subsidence line and for that matter the Tooley curve, by additional augering, interpretation and dating of the Yare valley alluvial stratigraphy. This could considerably improve the accuracy of the graph of the last 8000 years

of land-sea level changes in the lower Yare. It would not, for the reasons just quoted, necessarily increase the reliability of the projection into the future. Nevertheless even the present projection into the future should be of interest to those concerned with planning human reaction to land-sea level changes. If nothing more it is one possible future, and credible evidence that it is not likely to happen should be adduced before ignoring the possibility.

Acknowledgements

This interpretation of land-sea changes in the lower Yare valley was constructed whilst preparing some of the results of Dr.Brian P. L. Cole's University of East Anglia Ph.D. thesis for presentation at the International Association of Sedimentologist's international meeting on "Holocene marine sedimentation in the North Sea Basin" held at Texel in the Netherlands in September 1979. (It rests substantially on Dr. Cole's research and data but he is not responsible for this particular form of its interpretation.)

It was also to some extent provoked by a question put to me some months earlier by Mr. Bryan Read, who asked me whether there was in fact any reliable evidence for continuing subsidence in the Great Yarmouth area. At that time I replied that I did not think the evidence in the literature provided a coherent answer one way or the other. In a sense this paper is a more considered answer to his question.

Figure 1. Land-sea level changes in the lower Yare valley 8000 BP (= 6000 BC) to 2000 AP (= 4000 AD). The sea-level curve of Tooley (1978), obtained from a coastal area of no net subsidence or elevation, has been modified to incorporate a continuing rate of subsidence of 1.5 ka^{-1}. The resultant land-sea level curve has been applied to the lower Yare valley and correlated to alternations of freshwater and estuarine conditions in the valley from 8000 BP to the present-day. It is speculatively continued to the year 2000 AP.

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THE KIMMERIDGE CLAY IN NORFOLK

R.W. GALLOIS*

Introduction

The Kimmeridge Clay was first recognised as a separate formation by William Smith on his 'Improved Table of Strata' (1815-6) where he called it the Oaktree Clay. Webster (in Englefield 1816) subsequently used the term Kimmeridge Clay for the same beds, taking the name from the village on the Dorset coast where there are fine cliff sections. The formation has an extensive outcrop and subcrop in England. The outcrop runs in an almost continuous strip from Dorset to North Yorkshire and is broken only in north Dorset, Wiltshire, between Buckinghamshire and Cambridgeshire and across the Market Weighton axis in Humberside/ North Yorkshire, where the formation has been removed by erosion during the late Jurassic and Lower Cretaceous. The subcrop underlies the whole of the land area to the east of the outcrop with the exception of a large area beneath East Anglia (on the London Platform) and a smaller area on the Market Weighton Axis.

Throughout much of its outcrop the Kimmeridge Clay is largely obscured by drift deposits or weathered material and for this reason most of the important contributions to its stratigraphy have been made from studies of the Dorset cliff sections. The formation has had little economic value in the past. It has been used on a limited scale for brickmaking at many localities and much of the stratigraphical

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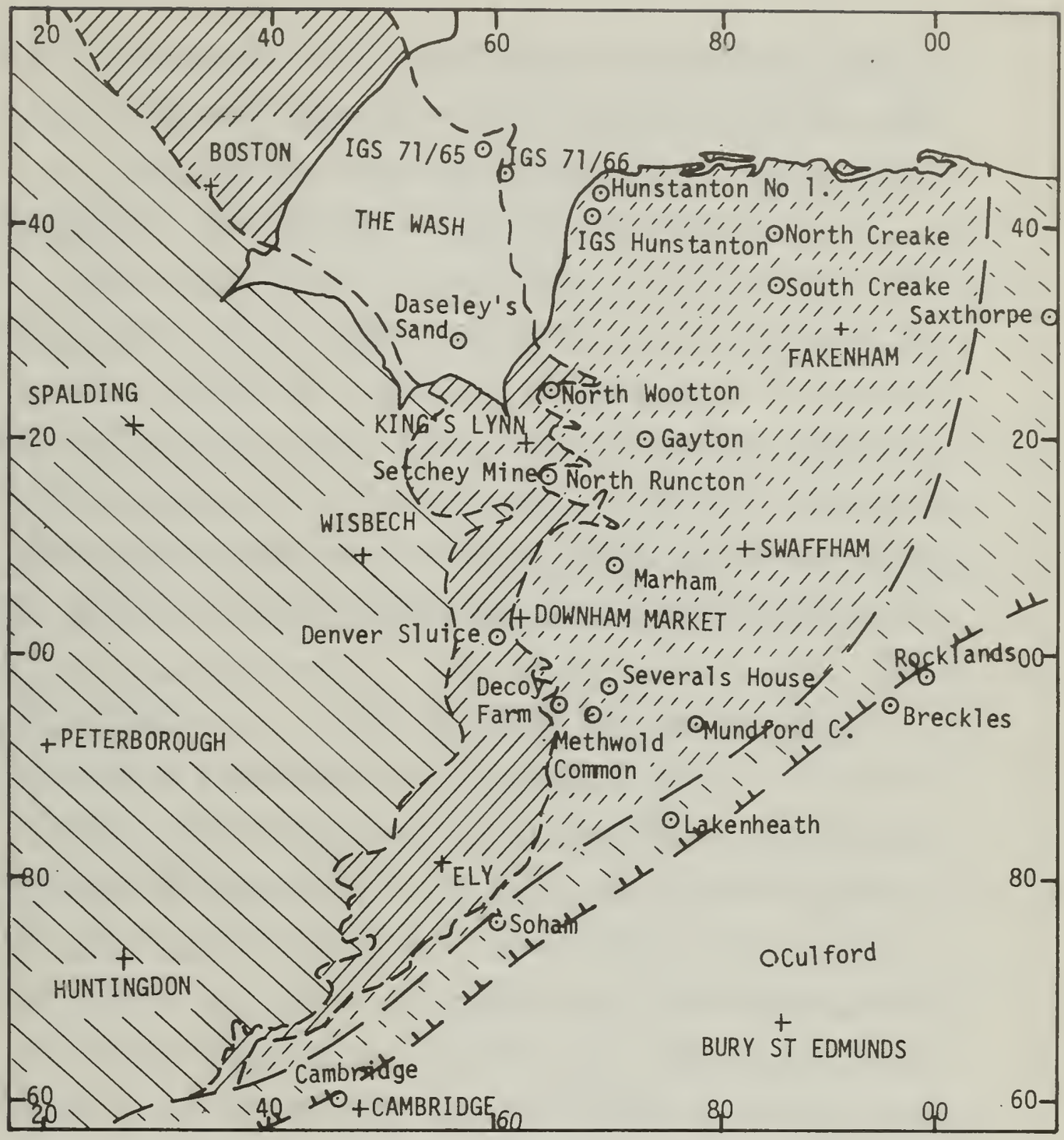
information obtained from inland areas has come from small pits dug for this purpose. Most of these are now completely degraded and, because of their geographical isolation from one another and from the Dorset coastal sections, the faunal and lithological material collected from them is stratigraphically useful only where the complete local sequence is known from continuously cored boreholes.

The most celebrated attempts to exploit the Kimmeridge Clay have been those which sought to extract commercial quantities of oil from the numerous thin seams of oil shale (kerogen-rich mudstones that yield appreciable quantities of oil when retorted at 400 to 500°C) which occur in the middle and upper parts of the formation. The occurrence of oil shales in the cliffs at Kimmeridge Bay has been known since Iron Age times. The most famous Dorset seam, the Blackstone, was used locally as a coal substitute, both domestically and industrially, and yielded at various times in the 16th to 19th centuries products ranging from lubricating oil to fertilizer and a sanitary deodorizer. Similar combustible shales have been recorded elsewhere in Dorset and in Wiltshire, Norfolk, Lincolnshire and Scotland.

The Kimmeridge Clay is poorly exposed in Norfolk and little detailed work has been done on its stratigraphy until relatively recently. The highest part of the formation crops out along the eastern edge of Fenland between King's Lynn and Southery but the bulk of the formation is overlain by the Pleistocene and Recent deposits of Fenland and The Wash (Fig. 1). Although temporary sections have become available from time to time in the outcrop they have usually



outcrop

subcrop

Borehole

probably removed by Cretaceous erosion

probably removed by post-Cretaceous erosion

probable depositional limit

Drift deposits omitted for simplicity

Fig. 1 Distribution of the Kimmeridge Clay in Norfolk

been deeply weathered and have produced little stratigraphical information. The lower part of the formation is everywhere covered by drift deposits within the county and is known only from boreholes.

The first published record of the Kimmeridge Clay in Norfolk was that of William Smith on his geological map of the county (1819). On this he noted that the "Oaktree Clay [Kimmeridge Clay] was part slaty and bituminous as at Kimmeridge in Dorset". Rose (1835, p. 175) subsequently recorded inflammable shales "that burned like cannel coal" in the Kimmeridge Clay in a brick pit at Southery [probably TL 617 958] and oil seepages, supposedly derived from the Kimmeridge Clay, were noted in the Puny Drain at Setchey, Norfolk [TF 626 145] (Forbes Leslie, 1917).

It was largely on the evidence of these seepages, and the possible prospect of finding oil shales comparable to those that had been worked at Kimmeridge, that oil-shale exploration was begun in Norfolk during the First World War. A pilot operation was set up at Setchey and more than 60 cored boreholes were drilled in the area between the Gaywood River at King's Lynn and the River Wissey at Hilgay, between 1916 and about 1923. The full-scale retorts at the Setchey works were never completed and a small mine and opencast pit dug for the pilot plant were closed. There was little activity after 1923.

Because of the secrecy surrounding these operations few details have survived from the majority of the boreholes. However, Pringle (1923) was able to examine and sample three continuously cored boreholes drilled in Methwold Fen in south-west Norfolk and until recently these provided the most detailed sections of the Kimmeridge Clay in the county.

Two of the boreholes, at Methwold Common [TL 679 941] and Severals House [TL 692 964], penetrated the full thickness of the formation. Pringle concluded from his palaeontological studies that the full sequence of Kimmeridgian zones appeared to be present in both boreholes. He suggested that the Norfolk Kimmeridge Clay was attenuated due to slow deposition since the boreholes proved about 38 m of beds that were the time-equivalent of about 500 m of beds in Dorset.

In 1970-71 the IGS drilled continuously cored boreholes at Hunstanton, Gayton and Marham and at two sites in the central part of The Wash and these provided sequences through the upper part of the Kimmeridge Clay. In the following year 20 cored boreholes were drilled through all or part of the Kimmeridge Clay in the area between the southern part of The Wash and Denver Sluice as part of the engineering feasibility study for the Wash Water Storage Scheme (Gallois 1979).

The search for hydrocarbons in East Anglia in recent years has provided a relatively accurate picture of the extent of the subcrop of the Kimmeridge Clay in Norfolk. The full thickness of the formation was penetrated by the North Creake Borehole (Kent, 1947) and subseqently by boreholes at Hunstanton and South Creake. Cretaceous rocks were proved to rest on pre-Kimmeridgian rocks in deep hydrocarbon boreholes at Saxthorpe, Rocklands, Breckles, Lakenheath, East Ruston and Somerton, in the deep IGS boreholes at Cambridge, Soham and Trunch and in old water supply boreholes at Culford and Lowestoft. Some of the more important boreholes to have penetrated the outcrop and subcrop are shown in Fig. 1.

Stratigraphy

The large amount of continuous core made available by the Wash Water Storage Feasibility Study enabled the stratigraphy of the Kimmeridge Clay of Norfolk, and in particular lateral variations in the sequence, to be studied in detail for the first time. The lithological and faunal sequences were found to be remarkably constant throughout the 500+ sq. km. of the study area and this enabled a standard sequence to be described consisting of 48 distinctive beds which were defined on the basis of a combination of lithological and faunal characters (Fig. 2 after Gallois and Cox 1976 and Cox and Gallois in Gallois 1979).

At its most complete the Kimmeridge Clay in Norfolk is about 130 m in thickness. It thins southwards from this maximum beneath the central part of The Wash to about 100 m at King's Lynn, 60 m at Downham Market and nothing in the Mundford area (Fig. 1). This thinning is made up of two components acting in the same direction. The first component is a contemporaneous attenuation in sedimentation as the London Platform is approached and the second is the overstep of the Sandringham Sands. Comparison of selected groups of beds in boreholes between The Wash and Denver Sluice has shown that the attenuation occurs without any noticeable change in lithology and without intraformational erosion.

The Kimmeridge Clay of Norfolk is made up of a complex sequence of small-scale rhythms. In the lower part of the Lower Kimmeridge Clay these rhythms consist of thin silts or silty mudstones overlain by dark grey mudstones which in turn are overlain by pale grey calcareous mudstones. In the upper part of the Lower Kimmeridge Clay and in the Upper Kimmeridge Clay the rhythms consist of brownish grey kerogen-rich

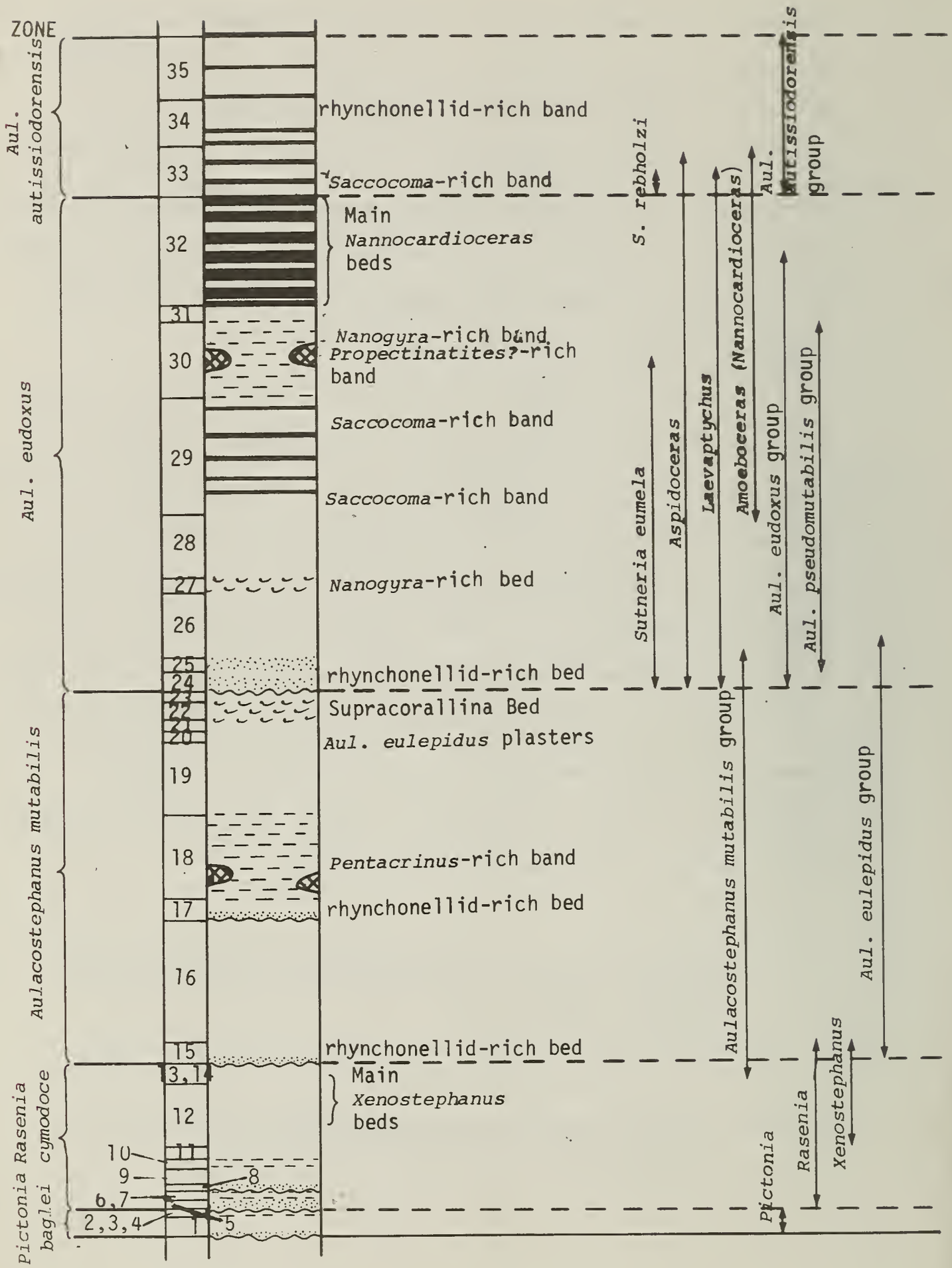
mudstones (oil shales) overlain by dark grey mudstones and then by pale grey calcareous mudstones, the last named sometimes including thin beds or doggers of muddy limestone (cementstone). Many of the individual rhythms and limestones can be correlated throughout Norfolk. Superimposed on this rhythmic sequence are broader lithological changes, from more to less calcareous and from more to less kerogen-rich, which can be regarded as larger scale rhythms and which can be correlated throughout the English Kimmeridge Clay.

The various lithologies are made up of a relatively small number of siliciclastic, bioclastic, biogenic and chemogenic components. The clastic materials are clay minerals (mostly illite and kaolinite), quartz, calcium carbonate in the form of microscopic and macroscopic shell debris and phosphatized fossil debris. The biogenic component consists mostly of calcareous fossils and of kerogen composed largely of diagenetically modified lipids probably derived in part from marine algae such as dinoflagellates. Diagenetically formed pyrite, phosphate and cementstone concretions make up the relatively small chemogenic component. The typical composition of some of the commoner Kimmeridge Clay lithologies can be summarized as follows:-

(i) dark grey mudstone - clay minerals 45 to 65%, quartz 10 to 30%, calcium carbonate 5 to 20% depending upon shell content, kerogen $< 1\%$

(ii) medium grey mudstone - clay minerals 35 to 55%; quartz 10 to 15%; calcium carbonate 20 to 35%; kerogen $< 1\%$

(iii) pale grey mudstone - clay minerals 25 to 45%; quartz 8 to 15%; calcium carbonate 25 to 55%; kerogen $< 1\%$


ZONE
Aul. autissiodorensis
Aul. eudoxus
Aulacostephanus mutabilis
Pictonia Rasenia baglei cymodoce
35
34
33
32
31
30
29
28
27
26
25
24
23
22
21
20
19
18
17
16
15
3,14
12
11
10
9
8
6,7
2,3,4
1
5
rhynchonellid-rich band
Saccocoma-rich band
Main Nannocardioceras beds
Nanogyra-rich band
Propectinatites?-rich band
Saccocoma-rich band
Saccocoma-rich band
Nanogyra-rich bed
rhynchonellid-rich bed
Supracorallina Bed
Aul. eulepidus plasters
Pentacrinus-rich band
rhynchonellid-rich bed
rhynchonellid-rich bed
Main Xenostephanus beds
S. rebholzi
Sutneria eumela
Aspidoceras
Laevaptychus
Amoeboceras (Nannocardioceras)
Aul. autissiodorensis group
Aul. eudoxus group
Aul. pseudomutabilis group
Aulacostephanus mutabilis group
Aul. eulepidus group
Pictonia
Rasenia
Xenostephanus

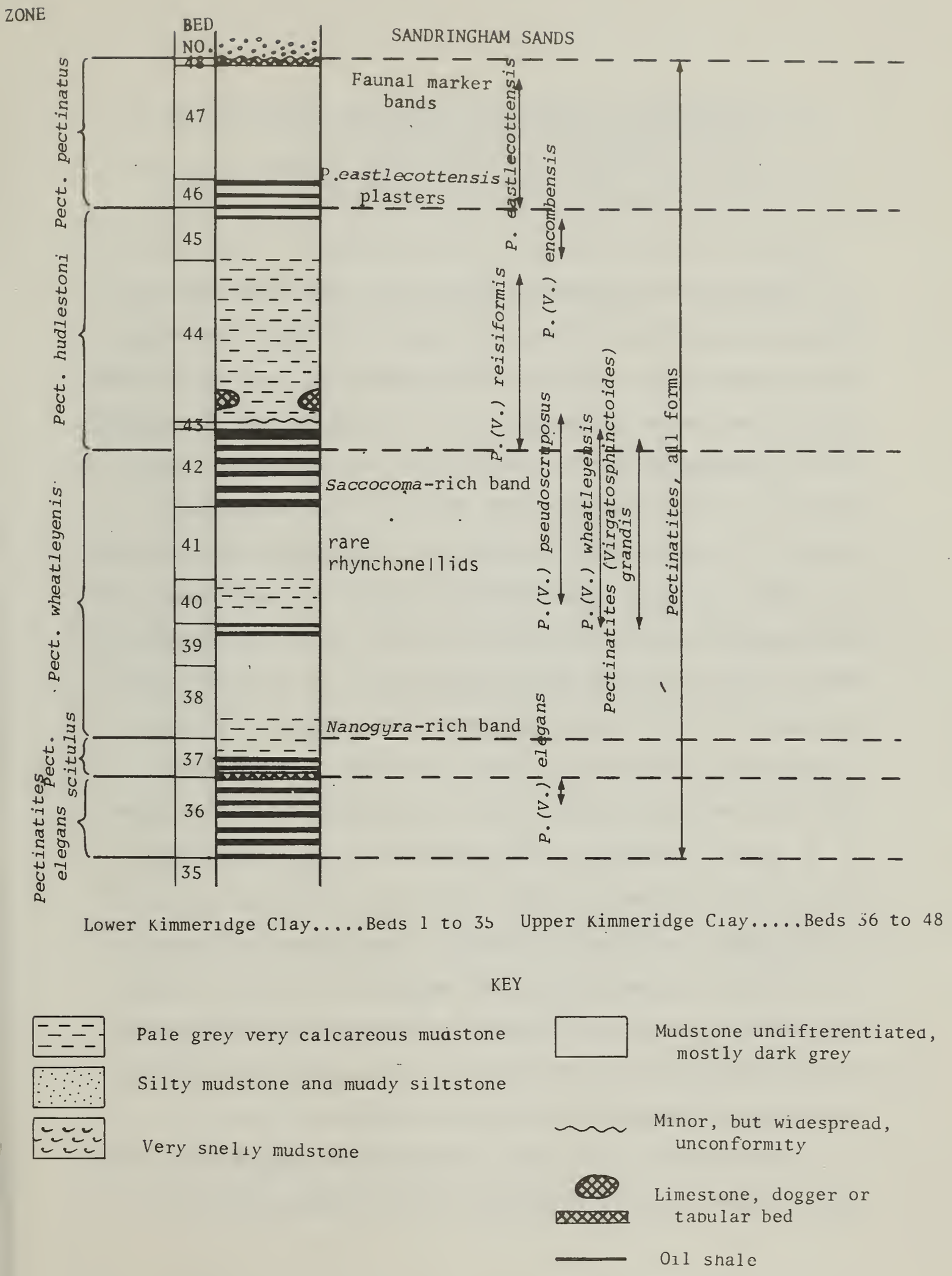


Fig. 2 Generalised vertical section of the Kimmeridge Clay of Norfolk

(iv) cementstone - clay minerals 10 to 20%; quartz 2 to 6%; calcium carbonate 60 to 90%; kerogen - 1%

(v) oil shale - clay minerals 20 to 40%; quartz 10 to 15%; calcium carbonate 10 to 25%; kerogen 10 to 45%

The two most distinctive Kimmeridge Clay lithologies that can be recognised in weathered sections at outcrop in Norfolk are muddy limestones and oil shales. Persistent tabular beds or closely spaced doggers of limestone occur in the mutabilis (Bed 18), eudoxus (Bed 30), scitulus (Bed 37), hudlestoni (Bed 44) and pectinatus (Bed 48) zones. Each of these can be recognised on the basis of either fauna or lithology. The Bed 18 limestones commonly enclose large Aulacostephanus with smooth body chambers (A. mutabilis (J. Sowerby)) and small, finely-ribbed forms (A. eulepidus (Schneid)); the Bed 30 limestones and adjacent mudstones commonly contain coarsely-ribbed Aulacostephanus of the eudoxus group, the large perisphinctid Propectinatites?, large forms of the oyster Nanogyra virgula (Defrance) and common serpulids. The limestones in Beds 37, 44 and 48 all contain similar pectinatitid and bivalve faunas but the first is a tabular, calcite-cemented oil shale, the second consists of large doggers and lies only 1 to 2 m above thick oil shales with Saccocoma (Bed 42) and the third only occurs beneath The Wash.

Limestone doggers occur in Beds 1, 4, 7, 8, 13, 15, 17, 23, 24, 34 and 40 but are too widely spaced to be confused with the five persistent horizons described above except in very small sections where the spacing of the doggers cannot be determined.

Thin seams of oil shale occur throughout the eudoxus to pectinatus zones inclusive but are concentrated in five main oil shale-rich

bands in the eudoxus (2), elegans, hudlestoni and pectinatus zones. A borehole at North Runcton [TF 6404 1624], drilled to examine the oil shales, proved 80 seams ranging from 1 to 47 cm in thickness (Gallois 1978). At outcrop the oil shales are usually much altered due to the interaction of the weathering products of their high pyrite content with their shelly fauna. When thus weathered they are usually fissile, parting along bedding planes encrusted with secondary gypsum [Ca $SO_4.2H_2O$] crystals and powdery natrojarosite [Na Fe_3 $(SO_4)_2$ $(OH)_6$.]. At some levels the oil shales are rich in phosphatized fish debris and faecal pellets and this may be the source of phosphorus that enables the brilliant blue mineral vivianite [Fe_3 $(PO_4)_2.8H_2O$] to form in some of the weathered oil shales. The organic (kerogen) part of the oil shales is surprisingly resistant to weathering and where the oil shale is only sparsely shelly it can be split to reveal well preserved calcareous and pyritic fossils.

The oil shale seams cannot be distinguished from one another except by their faunas and, even then, in only broad terms. The oil shales of the eudoxus Zone are rich in the small smooth or finely ribbed, keeled ammonite Amoeboceras (Nannocardioceras) and also contain Aulacostephanus, Aspidoceras, Amoeboceras (Amoebites), Laevaptychus and Sutneria. Those in the elegans to pectinatus zones contain forms of Pectinatites that are difficult to identify as crushed or incomplete specimens. The hudlestoni Zone oil shales are distinguishable at one level (Bed 42) by the presence of abundant pyritized plates of Saccocoma.

The Kimmeridge Clay contains a rich marine fauna dominated by bivalves and ammonites but with gastropods, belemnites, brachiopods,

serpulids and fish, reptile, crustacean and plant debris common at selected levels. Crushed but otherwise well preserved ammonites are common throughout the sequence and because they occur in assemblages of rapidly evolving forms provide an excellent basis for a zonal scheme. The ammonite faunas are dominated by perisphinctids, the zonal scheme being based on species of Pictonia, Rasenia, Aulacostephanus and Pectinatites (Fig. 2). Other ammonites are common in the Rasenia and Aulacostephanus zones, notably Amoeboceras, Aspidoceras and Sutneria, but in the overlying Pectinatites zones no ammonite other than Pectinatites has been recorded from Norfolk. Gravesia, which has been collected at this stratigraphical level in Dorset and Surrey and forms an important link with Kimmeridgian sequences elsewhere in Europe, has yet to be recorded in the county. The highest part of the Kimmeridge Clay, characterised by species of Pavlovia and Virgatopavlovia, is absent in Norfolk due to uplift and erosion in the late Jurassic but phosphatized, water-worn fragments of these ammonites occur in the basal pebble bed of the overlying Sandringham Sands.

Most of the non-ammonite macrofauna of the Kimmeridge Clay is made up of long-ranging taxa but some of these can be stratigraphically useful where they make a sudden appearance or where they occur in great abundance over a small vertical range. A number of faunal marker bands of this type have been identified in boreholes in Norfolk; a few have been recorded at outcrop and others might be expected to occur in the spoil from temporary excavations and drains.

Amongst the bivalves the small oyster Nanogyra virgula ranges from the mutabilis to the wheatleyensis zones but is especially abundant in

Norfolk in three thin beds, two in the eudoxus Zone and one in the basal wheatleyensis Zone. The highest band crops out or is overlain by only thin Recent deposits in the area between Wiggenhall and Southery and might be expected to occur in excavations there. In the Upper Kimmeridge Clay of the same area the bivalves 'Lucina' miniscula Blake, Protocardia morinica (de Loriol), Astarte and small oysters and the inarticulate brachiopods Discinisca and Lingula are common but are not diagnostic of any particular stratigraphical level.

Crinoids are rare in the Kimmeridge Clay except at one level in the mutabilis Zone where Pentacrinus columnals are abundant and at four levels, in the eudoxus (2), autissiodorensis and wheatleyensis zones, where pyritized plates of the tiny free-swimming Saccocoma occur in great abundance. Each of the Saccocoma-rich bands occurs in oil shale and, when fresh, the brass-coloured plates stand out in marked contrast to the dull brown of the oil shales. The highest of the four bands has been recorded at outcrop at Setchey and Downham Market. At both localities the pyrite is largely destroyed by weathering but the shape of the Saccocoma plates has been preserved in secondary gypsum overgrowths.

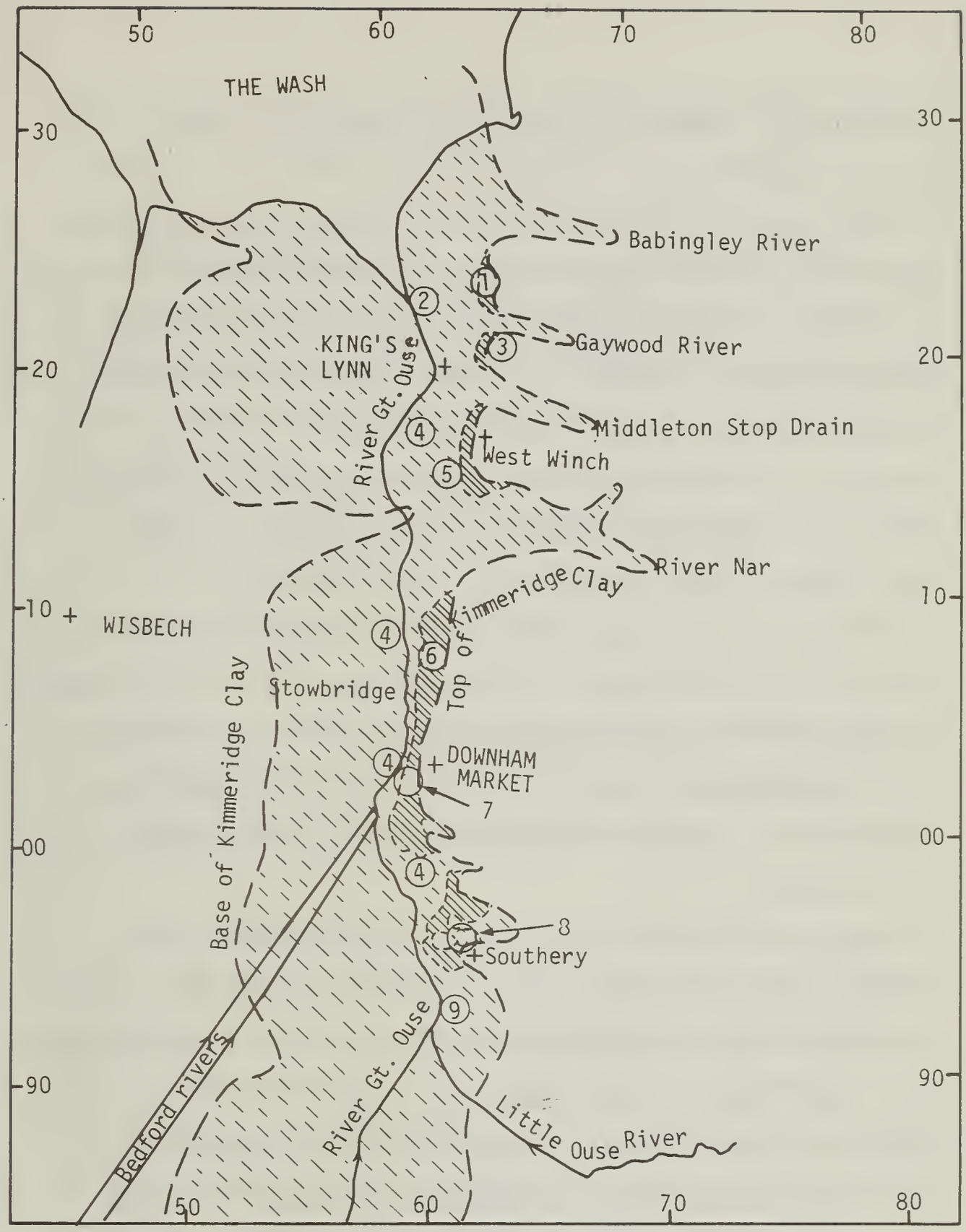
Rhynchonellid brachiopods are common in the muddy siltstones (Beds 15, 17 and 24) in the mutabilis and eudoxus zones. These beds are covered by thick drift deposits everywhere in Norfolk but loose blocks of the siltstones have been recorded from the local boulder clay. Rhynchonellids have also been recorded from the wheatleyensis Zone (Bed 41) in Norfolk but not in sufficient numbers for their stratigraphical distribution to be accurately known.

Details of sections

There is no natural exposure of Kimmeridge Clay in Norfolk at the present time nor is there any working clay pit that exposes any part of the formation. However, fragments of the more resistant Kimmeridge Clay lithologies, notably oil shales, cementstones and some of the harder mudstones, occur in the spoil at a number of localities where sections formerly existed, mostly at the sites of engineering works. When compared with the standard sequence shown in Fig. 2 these spoil fragments can provide useful stratigraphical information. The positions of the sections and their relationship to the Kimmeridge Clay outcrop and its subcrop beneath drift deposits are shown in Fig. 3. Beds 30 to 33 are present at shallow depths beneath Recent deposits in west Norfolk and should occur from time to time in drain spoil: Beds 34 to 47 crop out and will become available for study in temporary excavations.

In addition to the localities listed below Rose (1835) and Whitaker et al. (1893) recorded Kimmeridge Clay in brick-pits at Denver, Fordham, Watlington, West Winch and Shouldham Thorpe, but no description or material has survived from any of these sections. The last named locality is sited on boulder clay which rests at depth on Sandringham Sands and the brick pit, at Foddestone Gap [TF 652 089], was interpreted by Reid (in Whitaker et al. 1893, p. 63) as being in a 50 ft-thick erratic mass of Kimmeridge Clay within the boulder clay.

1. South Wootton; a small excavation dug for an electricity sub-station in 1972 at Chapel Lane, South Wootton [TF 6405 2318], close to the junction with the Sandringham Sands, proved about 1 m of weathered mudstone and



KEY

Kimmeridge Clay at surface

Kimmeridge Clay overlain by drift deposits

Other strata

(5) Section referred to in the text

Fig. 3 Geological sketch map showing positions of sections referred to in the text

oil-shale with fragments of finely-ribbed pectinatitid ammonites (probably Bed 46 or 47).

2. North Lynn; spoil from a 2 m-diameter sewerage tunnel which passed beneath the River Great Ouse at North Lynn [TF 604 227] in 1972 included large doggers of densely calcite-cemented oil shale together with mudstones and thin oil shales. The cementstone was a single impersistent bed that followed the axis of the tunnel for most of its length. The mudstones and oil shales contained '*Lucina*', *Protocardia*, *Lingula* and pectinatitid ammonites and suggest that the stone band is that which marks the base of the *scitulus* Zone (Bed 37) in Norfolk.

3. Fairstead Estate, King's Lynn; spoil from sewerage trenches [TF 642 194] dug for a new housing estate in 1966 showed the basal bed of the Sandringham Sands underlain by softened dark grey clay with thin oil shales. These shales included fragments of a soft, very pale brownish grey, coccolith-rich limestone with *Pectinatites (P.) eastlecottensis* (Salfeld) (base of Bed 46).

4. Fenland Flood Relief Channel; between Lynn sugar beet factory [TF 6050 1730] and St. Germans Bridge [TF 6084 1571] the spoil from the channel shows its floor to have been cut entirely in Upper Kimmeridge Clay. Loose doggers of cemented oil shale (Bed 37) occur near the sugar beet factory. Between St. Germans Bridge and Wiggenhall St. Mary Magdalen railway bridge [TF 6000 1025] the channel is cut in glacial deposits. From there southwards the floor of the channel is again entirely in Kimmeridge Clay. Lower Kimmeridge Clay, consisting of oil shales with abundant *Nannocardioceras* (probably Bed 32 or 33), comes to the surface in a gentle anticline between Wiggenhall St. Mary

Magdalen and Stowbridge [TF 605 070]. These are the oldest strata recorded at the surface to date in Norfolk.

Successively higher levels of the Upper Kimmeridge Clay can be recognised in the spoil between Stowbridge and Downham Bridge [TF 601 033]. At this last locality the following section is exposed in the east bank of the channel for some 200 m north of the bridge at times of low water:

Bed 44: Pale grey, uniform, almost barren clay, softened and weathered; discontinuous line of large cementstone doggers 1.0 m above base; sharp base to unit .....1.40 m

Bed 42: Oil Shale, shelly, fissile, deeply weathered with rotted bivalves and ammonites and pyritized Saccocoma; interbedded with dark grey fissile shelly clays .....cl.1 m

The combined presence of Saccocoma and Pectinatites in the oil shales is diagnostic of Bed 42 and the overlying pale grey clays and cementstone of Bed 44. A similar, but less well exposed section, occurs in the north bank of the Cut-Off Channel at Fordham [TL 607 996]. This latter locality has yielded a specimen of Rhynchonella subvariabilis Davidson (Sedgwick Museum, Cambridge) one of the few records of an articulate brachiopod in the Upper Kimmeridge Clay in Norfolk.

The Upper Kimmeridge Clay spoil from the Flood Relief and Cut-Off channels between Downham and Fordham has also yielded numerous ichthyosaur and plesiosaur vertebrae (much prized as ash-trays by

local farmers) and fragmentary reptilian bones. An almost complete icthyosaur skeleton from Stowbridge has been described as a new form, Grendelius mordax, by McGowan (1976). Beds 40 to 46 were probably exposed at the time of excavation of the Cut-Off Channel between Downham Market and the junction with the Sandringham Sands near Snowre Hall, Fordahm [TL 631 996]. Only Beds 42 and 44 can still be recognised with confidence.

5. Setchey; contemporary photographs of the small opencast pit dug for oil shales in about 1920 at Setchey [TF 6268 1452] suggest that it was in an oil shale-rich band (Bed 42) in the wheatleyensis Zone and that the overburden included the pale calcareous mudstones and cementstones of Bed 44. This suggestion was supported by the observations of the late Dr. J. Pringle who obtained samples from the pit in 1917 via a testing works at Chiswick. The fauna of the oil shales included Saccocoma and pectinatitid ammonites and enabled Pringle (unpublished MSS 1919) to correlate the Setchey seams with the Blackstone of Dorset. In 1975 IGS made a temporary excavation in the northern side of the pit to examine the weathering profile of the shales and to obtain samples for chemical analysis. The following section was measured:

Pleistocene deposits: cryoturbated flint gravel, ferruginous sand and sandy clay (derived largely from the Kimmeridge Clay) .....1.9 m

Kimmeridge Clay Bed 44; pale and medium grey, deeply weathered calcareous clays with a line of cementstone doggers in lower part of bed; shelly in part with rotted bivalves and ammonites; sharp planar contact with bed below disturbed by burrows .....1.6 m

Bed 43; very dark grey, apparently barren clay softened by weathering .....0.16 m

Bed 42; oil shale, dark brownish grey with brown streak; fissile, shelly with abundant '*Lucina*' *miniscula* and rarer *Protocardia*, small oysters, *Discinisca* and fragments of *Pectinatites*; fish debris and faecal pellets locally common; *Saccocoma* abundant at one level; interbedded in 5 to 30 cm-thick seams with sparsely shelly dark grey clays .....1.7 m seen

The oil shale were well jointed and yielded large quantities of water that made it impossible to deepen the excavations.

The oil shales seams which were worked in the Setchey opencast pit crop out in the banks of the Puny Drain [TF 626 145] about 100 m west of the pit. There is currently no exposure but large amounts of deeply weathered oil shale are present. Most of the calcareous fossils and all the pyritised fossils in the shale are completely rotted.

In his account of the oil shale workings Forbes-Leslie (1917, p. 18) referred to a mine [TF 625 145] that was overcome by an inrush of oil-covered water. It is unlikely that this mine ever worked oil shale since it seems to have been abandoned for financial reasons during the construction stage. The layout of the mine, as shown on the Ordnance Survey 25-inch scale map of 1925, consisted of two shafts and an engine house. One of these shafts was open until about 1970 when it was back-filled by the local landowner who measured the depth at that time as approximately 15 m. The small amount of spoil still present consists largely of dark grey shelly mudstone with thin oil shale seams. The faunal assemblage, mostly '*Lucina*', *Protocardia* and *Pectinatites* fragments, together with the depth of the shaft, suggests that the

seams encountered were those of the elegans Zone (Bed 36).

Forbes-Leslie (1917, p. 16-17) recorded at least three 6 ft-thick oil-shale seams in the Kimmeridge Clay of the Setchey area but no such seam has subsequently been recorded.

6. Stowbridge; extensive workings in Pleistocene flint gravels at Stowbridge [TF 614 073] have revealed the irregular weathered surface of the Kimmeridge Clay. Spoil from the clay includes pale grey calcareous mudstones, cementstone doggers and thick oil shale seams. This combination of lithologies, when taken in conjunction with the nearby Flood Relief Channel sections, indicates the presence of Beds 42 and 44.

7. Downham Market; Whitaker et al. (1893, p. 47) recorded a brick-pit in the Kimmeridge Clay close to the railway station [TF 604 030] where 30 ft (9 m) of clays were worked above a floor of cementstone septaria. The section is now overgrown but the position of the pit suggests that it worked the calcareous clays of Bed 44 and that the cementstone in its floor is the same as that which crops out in the Flood Relief Channel at Downham Bridge. A similar cementstone, probably the same band, was noted by Whitaker et al. (loc. cit.) in the foundations of the nearby gasworks.

8. Southery; Rose (1835, pp. 174-5) recorded a brick pit at Southery [probably TL 617 958] and noted that it exposed 13 ft (4 m) of 'brick-earth' underlain in the floor of the pit by a 2 to 3 in-thick seam of inflammable shale. The bulk of the pit is in pale grey clays with cementstone doggers (Bed 44) and is at the same stratigraphical level as locality 7. It was presumably this calcareous clay that gave rise

to the yellow stock brick that is much in evidence in the Victorian and Edwardian parts of Downham Market and Southery. The underlying oil shales are those of Bed 42. Recent excavations for the Southery Bypass [TL 616 946] showed pale grey calcareous clays (Bed 44) overlain by chalky boulder clay rich in local Upper Jurassic and Lower Cretaceous debris. Fitton (1836, p. 316) collected two characteristic Lower Kimmeridge Clay fossils at Southery, the large flat oyster Deltoideum delta (Wm. Smith) and Laevaptychus, the aptychal plate of Aspidoceras. D. delta is known only from the Ampthill Clay and the basal beds of the Kimmeridge Clay: Laevaptychus only from the mutabilis to autissiodorensis zones (Beds 18 to 33) of the Kimmeridge Clay. The oldest Kimmeridge Clay at outcrop on the 'island' of Southery is in Bed 42 and could not be the source of these fossils. However, both fossils have thick calcitic shells and are common in the boulder clay of west Norfolk.

9. Southery; spoil from the foundations of a new (1977) pumping station at the junction of the Engine Drain and the Great Ouse [TL 6128 9318] included cementstone doggers and mudstones with fragments of Aulacostephanus and abundant Nanogyra virgula (probably Bed 30). The Recent deposits of this part of Southery Fens are thin and many of the deeper drains lying on either side of the Great Ouse have cut into the weathered upper surface of the Kimmeridge Clay.

Conclusions

The stratigraphy of the Kimmeridge Clay beneath Fenland and in its subcrop beneath the Sandringham Sands in Norfolk is known in detail from continuously cored boreholes. By contrast, little is known about

the stratigraphy at outcrop other than the stratigraphical positions of a small number of marker bands recorded in old brick-pits and temporary excavations.

Only the upper part of the Kimmeridge Clay crops out in Norfolk, but even within this limited sequence there are stratigraphical problems that cannot be solved by boreholes alone. Because of their small diameters (mostly 80 mm to 110 mm) borehole cores are unsuitable for determining the stratigraphical ranges of the less common parts of the faunal assemblage and those species that are large in relation to the core-diameter.

The distribution of rhynchonellid brachiopods in the Upper Kimmeridge Clay is a good example of the problems associated with the rarer elements of the fauna. Rhynchonella subvariabilis Davidson has been recorded at approximately the same stratigraphical level (Bed 41) in two boreholes in Norfolk. Other boreholes in the county that have penetrated the same bed have failed to yield brachiopods and it is not known whether the specimens collected represent isolated occurrences or whether they are part of a widespread marker band in which the brachiopods are thinly distributed. The pectinatitid ammonites upon which the zonation of the Upper Kimmeridge Clay is based are mostly greater than 75 mm in diameter (some 350 mm diameter) and complete specimens are rare in borehole cores. Their identification at species level depends, in most cases, on counting the number of ribs on complete, mature specimens. In consequence many species are known from only a single identifiable specimen (see Gallois and Cox 1974, Fig. 3 for examples). The stratigraphically important ammonite Gravesia has yet to be recorded in

Norfolk even though the beds in which it would be expected to occur have been penetrated by numerous boreholes and despite the fact that these beds crop out in the Stowbridge area.

An extreme example of large fossils in the Kimmeridge Clay are the ichthyosaurs and pleisosaurs. Fragments of these marine reptiles are common in the spoil from most excavations in the formation but their stratigraphical distribution in the area is completely unknown.

The stratigraphical sequence summarized in Fig. 2 should not therefore be regarded as a final answer, but merely as a temporary model that enables new data to be interpreted and incorporated into future better, but probably equally temporary, models. A comprehensive collection of lithological and faunal specimens from the Kimmeridge Clay of Norfolk is housed in IGS collections in London. These can be consulted by appointment. In addition, the author or his colleagues would be pleased to attempt to identify any specimens collected from temporary exposures in Norfolk. Good hunting.

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Bull. geol. Soc. Norfolk, 31, (September 1979)

KIMMERIDGE CRAWL: FIELD TRIP TO WEST NORFOLK, SUNDAY, 9 SEPTEMBER 1979

B.M. FUNNELL*

Four cars and eight persons starting from the Norwich area, and six cars and more than a dozen members and friends from the Kings Lynn area, met at 10.15 am. at Denver Sluice for a day of collecting and clambering over Kimmeridge Clay exposures.

Activitities started in earnest near Southery pumping station (TL 612932) where fresh spoil, including Kimmeridge Clay, had recently been taken from the Southery Main Drain alongside Sedge Fen road. Vertebrae, bivalves, oil shale and pieces of "beef" were found. More oil shale was found freshly excavated at the W side of the White Bridge (TL 616944), but freshly dumped foundation for the Southery by-pass that takes off westward from the old line of the A10 at this point had been rolled during the week and only a few of the large Pectinatites in it could still be seen.

Lunch was taken beside the river Wissey at Hilgay and the first stop in the afternoon was beside Downham bridge (TF 601033), where the large cementstone doggers of Bed 44 in the Upper Kimmeridge Clay could be seen in the E bank of the Relief Channel immediately N of the bridge. Mr. J.E. Clarke, Clerk to the Southery Internal Drainage Board then took us to see new excavations at Stow pumping station (TL 598057) where some really oily shale had been brought to the surface with some large ammonite specimens in it. There were also some interesting blocks showing patches of the brilliant blue mineral vivianite scattered around. More ammonites, an occasional vertebra, and good septarian nodules and cone-in-cone structure were found on the spoil from the freshly excavated 16 foot Drain nearby (extending towards TL 595055).

*School of Environmental Sciences, University of East Anglia, Norwich NR4 7TJ

The party continued to Stowbridge, where, in spite of the high water level, ammonites were obtained from some more cohesive blocks on the W bank just S of the bridge over the Relief Channel (TF 605 070).

Time prevented the party continuing to view the old shale workings at Setchey (TF 626 146), but it was generally agreed that the collecting and the fine warm September day had been enjoyed by all. We are all grateful to Ramues Gallois and members of the West Norfolk group who provided notes to help plan the day and to John Clarke, who guided us around the Internal Drainage Board's works.

BMF

Bull. geol. Soc. Norfolk, 31, (September 1979)

FIELD MEETING AT BRAMERTON COMMON, SEPTEMBER 3rd 1978.

P. CAMBRIDGE*

The Norwich Crag at Bramerton has attracted a great deal of attention since the ealiest days on account of the rich fauna of molluscs, fishes and mammals, and in recent years the foraminifers and pollen. It was visited by the great William Smith and specimens from this area were illustrated in Sowerby's "Mineral Conchology". At the present day remains of two old pits can be traced, Blake's Pit (TG 298060) to the east and the Common Pit (TG 295060) to the west. Traces of shelly material were seen in house foundations as far as the "Wood's End". To the west of this the Crag beds appear to have been cut out by Glacial or post-Glacial beds, as shown in the gas pipeline trench, a few hundred yards to the west. This trench was cut from river level to the top of the hill with no trace of Crag. Beds with a similar fauna to that at Bramerton occurred in excavations for the new sewage plant at Whitlingham but on examination were seen to be redeposited material and no Crag was seen in situ, so the disturbance of the Crag beds continues at least as far as the sewage plant. A little further to the west the Crag is again seen in the Great Pit, close to the bend in the river a Whitlingham, and here the surface of the Chalk is much higher and the shelly sands reduced in thickness. On the other side of the river, an old pit at Postwick Grove exposes some Chalk, and Crag shells are thrown out by rabbits. Some Crag was visible in 1951 but the pit is now much overgrown and infilled. However, examination of shells from a disturbed slope showed a fauna similar to that at Bramerton.

The first description of the Bramerton area seems to be that given by Richard Taylor (1823) who also gives a delightful sektch of a pit at Bramerton, probably that now known as the Common Pit, with a detailed section and list of species. The area was described slightly more fully by S. Woodward (1833) and since this work is now rare the description may be worth repeating:

*258 Bluebell Road, Norwich.

"At Bramerton, the shells may be traced in the bank on the right hand for a quarter of a mile as you approach the Wood's-end house. The cliff is situated about a quarter of a mile below the house by the river side: and, about two hundred yards down the river, a thick bed has been cut through to enlarge a cottage garden."

It would appear that at this date the river ran closer to the side of the hill and that much of the present Common is made ground. A list of about 92 species is given and two plates of Crag fossils are illustrated including examples of the monstrosities of Nucella and Littorina and some fish bones later described by Agassiz, although the latter's illustrations are far inferior to those of S. Woodward. Extensive collections, now in the Castle Museum, were made by a local geologist, James Reeve, who communicated a list of 111 species to the Norwich Geological Society (1878). His list is divided into an upper and lower bed for Bramerton Common but gives no indication of horizons for Blake's Pit.

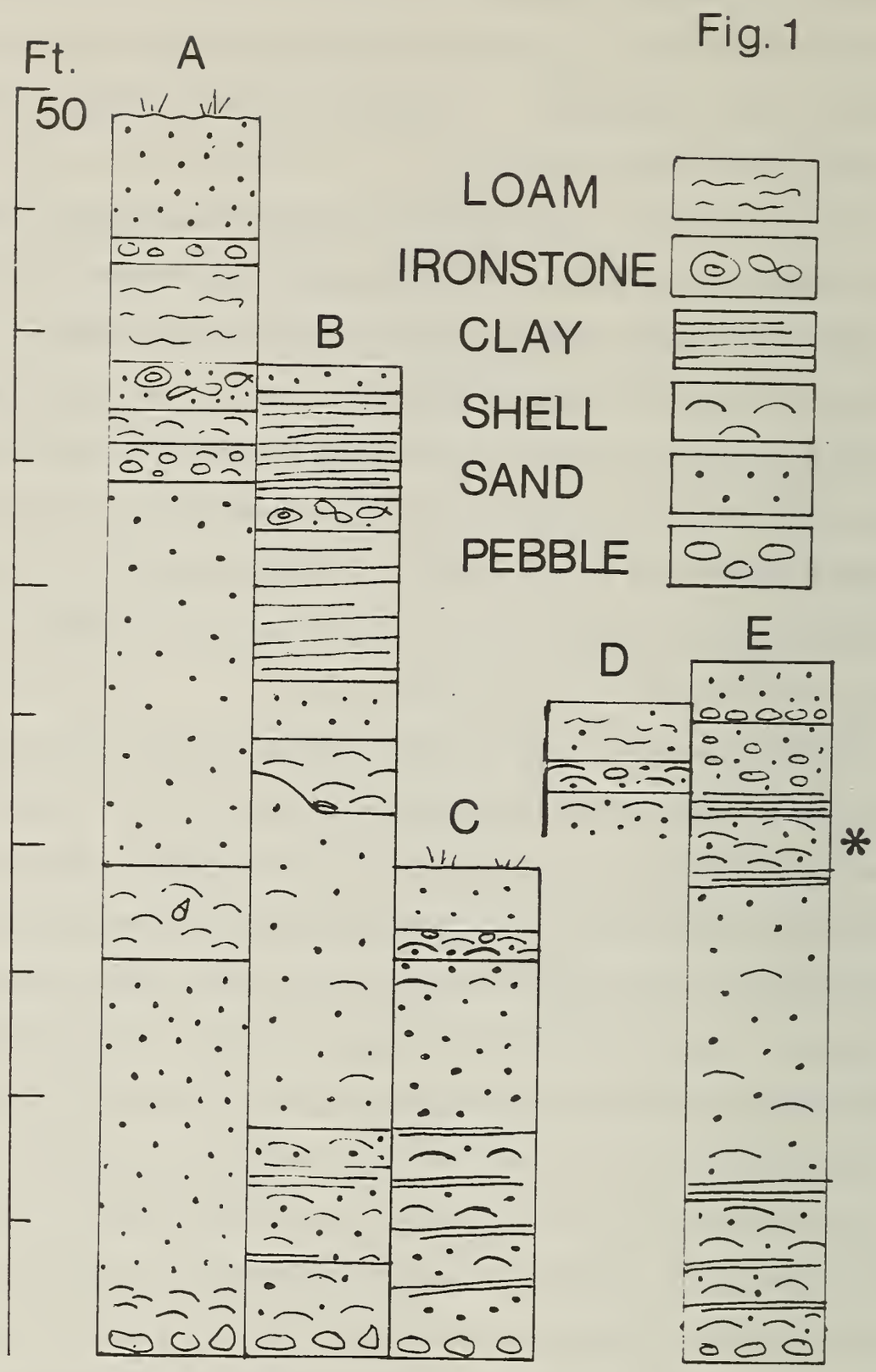
A brief description of Blake's Pit is given by Wood (1865) and Wood and Harmer (1872) in which the lower bed is described as Fluvio-Marine Crag, with a marine facies above, the upper part of which was called the Chillesford Shell Bed. In the Survey Memoir, H.B. Woodward (1882) gives some notes and a section at Bramerton Common plus a brief description of Blake's Pit, which appears less accurate than the earlier description by Wood.

There then appears to be a considerable gap in research on the area of over half a century, until 1958 when a section in the Common Pit was re-excavated by Funnell (1961) during an investigation of the foraminiferal fauna. At a meeting of the British Association (1961) the present author led a party to examine this new section but by an accident of navigation the party actually examined Blake's Pit. The only exposure at that time was at the top of the pit where a badgers sett had exposed very shelly Crag. Typical monstrosities of Nucella and Littorina were collected. On subsequent visits this bed was extensively sampled by the author and visited by a number of parties, extending the small exposure of the shell bed. In 1974 Blake's Pit

was re-excavated by the Geological Society of Norfolk and the lower part of the section exposed for the first time for many years. The warmer aspect of the fauna in the lower beds was confirmed, as well as the wealth of non-marine mollusca. The latter included one new genus, not hitherto recorded from northern Europe, Parmacella. The presence of small examples of derived Pliocene fossils was also noted.

A notable feature of the description of sections in the Bramerton area is the variation in thickness of the Crag given by different authors (see Fig. 1). In Blake's Pit, which does not show the full sequence, there is a maximum thickness of 27 feet (Cambridge/Markham). In the Common area measurements varied from just under 40 ft (Funnell)? to just under 50 feet (Taylor, 1824) and even 60 ft (Woodward,1833).Taylor also recorded three shell beds where other authors record two. The excavation in 1978 was intended to investigate these differences and also to see if the shell bed in Blake's Pit with its unusual fauna, could be traced into the Common area.

The new section was dug at a point judged to be close to that made by Funnell and the first 15 feet corresponded closely to his published section (Zone BIII), with no visible fossils. At this depth a shell bed was reached with a very pebbly matrix. Funnell and Woodward record an Upper Shell Bed with a sandy matrix; Taylor records a pebbly bed. These differences probably represent a lateral variation in lithology, common in such shallow water deposits. Most of the published sections agree that below the shell bed are a series of sands with few or no shells. Similar sands were excavated for a further 12 feet but at this depth the loose scree through which the trench was being dug commenced to collapse. Despite intense efforts to continue the short distance needed to expose the next shell bed, the collapse became too general and that part of the dig had to be abandoned. A small trench dug a little to the right also exposed the pebbly facies of the Upper Shell Bed and samples were taken from both sites. An attempt to expose the chalk at the base of the pit was also unsuccessful. A seven foot deep trial hole showed only



Sections in the Crag at Bramerton according to various authors, somewhat simplifie

A. Common Pit after R. Taylor

B. Common Pit after B.M.Funnell

C and D. Blake's Pit after P. Cambridge

E. Common Pit after H.B.Woodward, with (*) Zone of Astarte borealis.

disturbed material although the surface of the chalk should actually stand higher than the base of the pit.

The exposure of the lower part of this pit is very desirable but owing to the height of the original face and the consequent thickness of loose scree, this will be a major task unless a mechanical excavator is used.

Palaeontology of the Upper Shell Bed

Bivalves predominated, especially Macoma obliqua and to a lesser extent M. calcarea, Yoldia myalis, Mya sp and Astarte borealis. This would be the 'Zone of A. borealis' of earlier authors. Like the Upper Shell Bed of Blake's Pit there is a northern element in the molluscs but there are also considerable differences. No distorted or monstrous forms of Nucella and Littorina were seen. The Nucella were of the short rounded form characteristic of recent open coasts whereas in the Upper Shell Bed of Blake's Pit elongate forms associated with estuaries at the present day dominate. The change in shape of Nucella, the increase in the number of teeth of rays and other fishes, and the decrease in the number of non-marine shells in the Upper Shell Bed of the Common Pit all point to a change in this area from enclosed estuarine deposits to those of a more open shore line.

Faunal List, Upper Shell Bed, Common Pit

Acila cobboldiae (J. Sowerby)	X	M. obliqua (Sow)	X
Anomia sp (S.L.	X	M. praetenuis (Wood)	X
Arctica islandica (L)	3	Modiolus sp	XF
Astarte sp.	X	Mya (Arenomya) arenaria L	X
A. borealis (Schumacher)	X	Mya truncata L	X
A. montagui (Dillwyn)	X	Mytilus edulis L	4F
Cerastoderma edule (L)	X	Paphia rhomboides Penn.	1
Chlamys opercularis (L)	1	Phacoides (Lucinoma) borealis (L)	1
Corbula (Varicorbula) gibba (Olivi)	X	Scrobicularia plana (Da Costa)	3F
Divaricella sp	1F	Spisula sp	X
Ensis sp	2F	Thracia sp	3
Hiatella arctica (L)	X	Venus ovata Penn.	1
Macoma calcarea (Gmel)	X	Yoldia myalis (Couthouy)	X

Boreoscala sp	1F	Cliona sp	X
Calyptraea chinesis L.	X	Balanus balanus L	X
Gibbula tumida (Mont.)	X	Irregular echinoid spines	X
Littorina littorea L.	SF	Regular echinois spines	X
Naticid borings	X	Crustacean claws	X
Neptunea antique (L)	2	Raja sp dermal tubercles	1
Nucella lapillus (L)	X	Raja sp teeth	1
Ringicula ventricosa (Sow)	3F	Sparid teeth	X
Turritella sp	2F	"Platax" aggregate	X
Viviparus medius (Wood)	1	Fish teeth, vertebrae and bones	X
Chiton valve	1	Vole teeth and bones	3
Hemithyris psittacea (Chemn)	2		

Derived Chalk fossils include belemnite guards, echinoid spines, a rhynchonellid etc.

Among the rock and mineral types were flint pebbles (dominant), bored chalk pebbles, jasper, chalcedony, milky quartz, a terminated crystal of rose quartz, and quartzites.

Key to list.

X = present

F = present only as fragments

Below five specimens the acrual number of examples is given.

Note

In order to achieve consistency Imperial measures have been used throughout since most of the original sources quoted are in feet and inches. Some authors measured to the nearest six inches, others to the nearest foot. (1 foot equals 0.305 metres).

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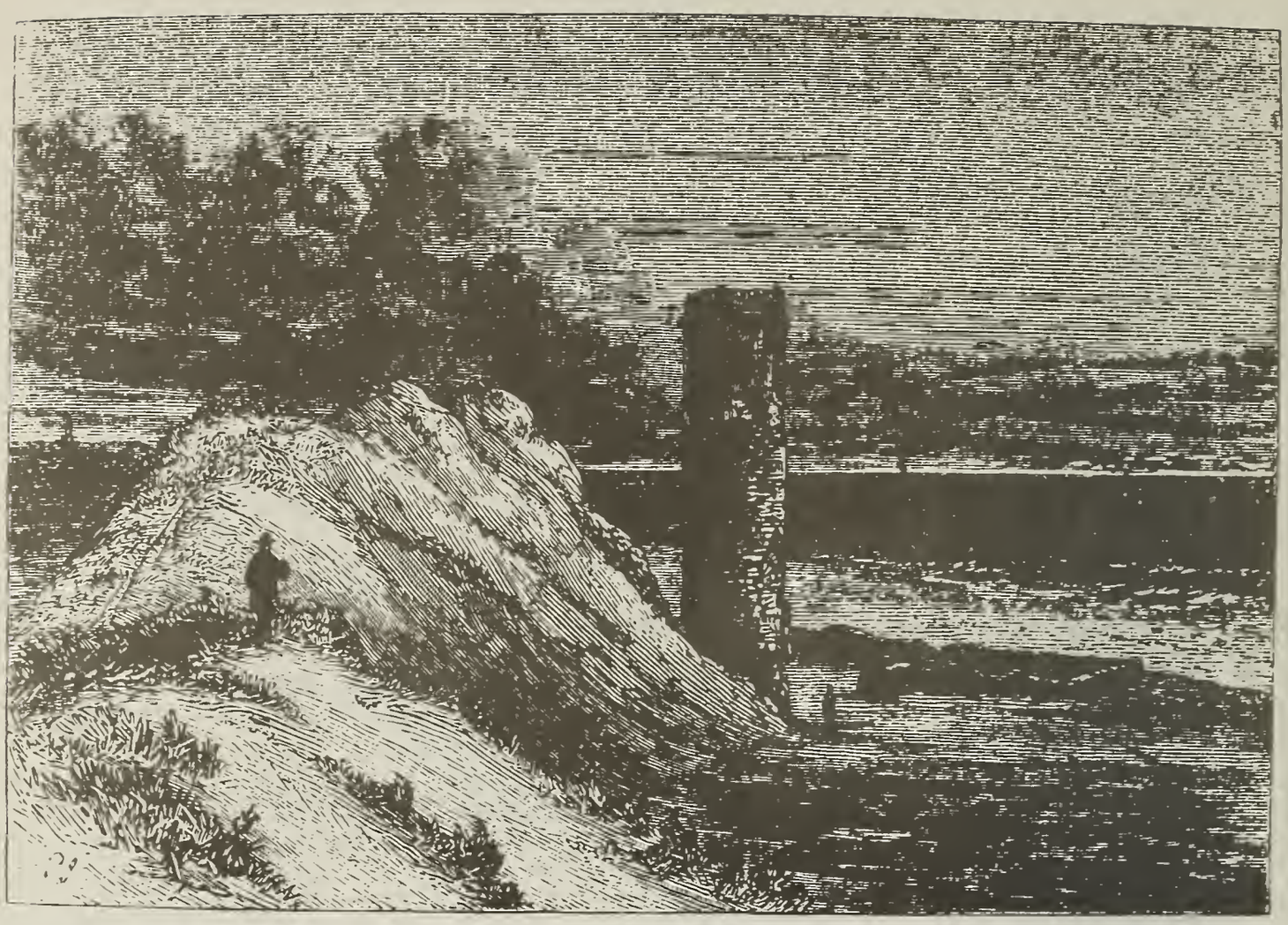

"Eccles Tower as it appeared after the storm of November 1862, from a drawing by Rev. S.W. King". Taken from Fig. 43 (p. 515) of Lyell's "Principles of Geology", 1867 edition, (see cover of this Bulletin). It seems that the problems of coastal erosion in parts of East Anglia have been recognised for a long time for "as early as 1605 the inhabitants (of Eccles) petitioned James I for a reduction of taxes, as 300 acres of land and all their houses, some fourteeen, had then been destroyed by the sea" (op. cit. p. 513).

SECRETARY'S REPORT FOR 1978

In addition to the summer field meetings the programme consisted of five evening lecture meetings, the Annual General Meeting and two afternoon "Collectors' Sessions" as follows: January, Dr. A.J. Stuart, 'Recent Research on Forest Bed Mammals';February, A. Collectors' Session for identification of specimens and Dr. J. Guest, Extra Terrestrial Geology; March, Mr. P.J. Lawrence, 'Bones for Beginners'; October, Mr. R. Markham, 'A Review of Some Recent Crag Exposures in East Anglia';November, The Presidential Address by Dr. G.S. Boulton on 'The Glaciation of the North Sea Basin'; December, a Collectors' Session and the A.G.M. which was followed by a showing of slides taken at field meetings during the year and a guided tour behind the scenes at the Museum.

The talk by Dr. Guest was given as a joint lecture for the G.S.N. and the Norwich Astronomical Association and was held at the University. All other meetings were at the Castle Museum.

The innovation of the Collectors' Sessions held on Sunday afternoons at the Castle Museum was made possible by Peter Lawrence and thanks are due to him for suggesting the idea and providing the facilities so that members of the public as well as G.S.N. members could bring specimens for identification or showing to others. I hope that these events might become a regular part of the Society's programme in future.

There were three committee meetings during the year.

This year sees the end of a three year stint on the Committee by both Mrs. Evans and Mr. Peake. I would like to thank them very much for their help and advice and for giving up their valuable time to attend.

This year also saw the subscription being raised to £1.50. However this was the first raise that has occurred for some years and although it was regrettable I think it was fairly generally agreed that it represents good value in that the Winter Lecture Meetings and the Summer field meetings together with the Bulletin offer members a fairly wide range of interest throughout the year. I hope however that as always people will let one or the other committee members know of areas or subjects of interest which could be covered in future.

The committee for 1979 is as follows:

Secretary:	Dr. C.J. Aslin
Treasurer:	Mr. P.G. Cambridge
Editor:	Dr. P.N. Chroston
Field Meeting Secretary:	Mr. P.J. Lawrence
Committee Members	Mr. D.J. Allen
	Mr. N.E. Dean
	Mrs. A. Horsfield
West Norfolk Member:	Mr. A.G. Barnes

Christopher J. Aslin, December 1978.

EDITORIAL NOTE

The Bulletin of the Geological Society of Norfolk seeks to provide an opportunity for the publication of research papers, notes, or general articles which are relevant to the geology of Norfolk in particular, or to East Anglian geology in general. The Society is also prepared to consider articles of general geological interest for publication, but normally they will be expected to include some local relevance. There are no restrictions on subject matter (apart from regional significance) and no formal restriction on length. We welcome full length research papers, short notes, and correspondence. All papers are normally refereed.

Potential contributors should note that we prefer manuscripts to be submitted in typewritten copy, and it would be helpful if the style of the paper in terms of capitalization, underlining, punctuation etc., would conform strictly to those used in the Bulletin. The reference list is the author's responsibility alone and should be checked carefully.

Illustrations should be executed in thin dense black ink line. Thick lines, close stipple or patches of black should be avoided as these tend to spread in the printing process employed. Original illustrations should, before reproduction, fit into an area of 225 mm by 175 mm. Full use should be made of the second (horizontal) dimension which corresponds to the width of print on the page, but the first (vertical) dimension is an upper limit only. Reproduction of photographs is normally possible provided there is adequate contrast.

All measurements in the script and illustrations should be in metric units.

I am happy to answer any queries concerning the suitability of a paper or any other editorial.

P.N. Chroston,
Editor,
University of East Anglia,
School of Environmental Sciences,
Norwich, NR4 7TJ.

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The Geological society of Norfolk exists to promote the study and knowledge of geology, particularly in East Anglia, and holds monthly meetings throughout the year. Visitors are welcome to attend the meetings and may apply for membership of the Society. For further details write to the Secretary: Dr. C.J. Aslin, University Library, University of East Anglia, Norwich NR4 7TJ.

Copies of the Bulletin may be obtained from the Secretary at the address given above: it is issued free to members.

The illustration on the front cover is taken from Figure 43 (page 514) of Lyell's "Principles of Geology", 1867 Edition, and shows the "Tower of the buried church of Eccles, Norfolk, A.D. 1839". The view shows "the inland slope of the hills of blown sand...with the lighthouse of Hapisburgh, N.W. of the Tower, in the distance". Lyell showed that in 1862 the sand dunes had moved inland, exposing the tower directly to the sea (see p. 78 of this issue).

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